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Design and Evaluation of a Differential Global Positioning System (DGPS) for the NPS Autonomous Underwater Vehicle (AUV)

by

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August 1999

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Accurate underwater positioning remains an important challenge to AUV researchers. Recent development of Differential Global Positioning System (DGPS) embedded in an AUV proved the capability of DGPS fixes to reduce the position error. By surfacing regularly, the AUV takes DGPS fixes and integrates them for position estimation. The purpose of this study is to develop a low-cost DGPS for the NPS AUV. To match mission requirements, the system is designed such that the differential receiver and the GPS receiver are two independent stations using radio modems to communicate. Local experimental testing showed that this system can yield positions within one to five meters accuracy.

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TABLE OF CONTENTS

LIST OF FIGURES

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I. INTRODUCTION

A. OVERVIEW

An essential aspect of an Autonomous Underwater Vehicle (AUV) control is navigation. Many potential applications require highly accurate navigation. There are many type and combinations of navigation that can be used by AUVs to determine their location. These types can be split into two categories: external signal-based navigation and sensor-based navigation.

External signal-based navigation provides positioning information only when the signal receiver is exposed to the signal, above the ocean surface, such as the Differential Global Positioning System (DGPS). Sensor-based navigation constitutes a self-contained system which can be made up a wide variety of equipment (Doppler sonar, gyroscope, compass, etc.) that can be used to sense interactions with the natural environment in order to determine the submerged location of an AUV.

A combination of DGPS and sensor-based navigation is needed to bound position-estimation error. Therefore, the implementation of a DGPS is required to enhance the inertial navigation system of the Naval Postgraduate School AUV. The motivation for this study is to design a low-cost simple DGPS with the current technology and equipment. To use such a DGPS everywhere in the world, local radio transmission of the differential signal will need to be considered.

B. ORGANIZATION OF THE REPORT

This report is organized into eight chapters.

Chapter II is a general overview of the frame of this study, the NPS AUV. It provides a description of the goal, the hardware and the software architecture of this vehicle.

Chapter III is a detailed problem statement. The problems related to the submerged navigation are briefly exposed and show the advantages of the DGPS.

Chapter IV is a description of the Global Positioning System. It explains the components and the different protocols used to compute position.

Chapter V is a description of the DGPS design as well as a presentation of the hardware used in the production of the system. Photographs of each piece of hardware are included.

Chapter VI details the format used for the transmission of the data and describes the software designed to get the position information from the GPS receiver.

Chapter VII presents the results of the experimental testing realized at the AUV research lab to determine the performance of the system.

The conclusions of the testing and recommendations for future work are provided in Chapter VIII.

II. RELATED WORK

A. INTRODUCTION

The applications of Autonomous Underwater Vehicles (AUVs) are subjects of increasing widespread interest by both civilian and military.

An AUV operates independently of any physical or electrical tether and requires little to no intervention from an outside activity. This type of vehicle is well suited for performing expensive and monotonous tasks such as ocean water quality and geological survey. AUVs could also be utilized for harbor and underwater inspection tasks and most importantly, mine countermeasures and neutralization, where there is a potential for loss of life. This last task is one of the goals of the Naval Postgraduate School (NPS) AUV Phœnix and as it is the frame work of this project, this chapter provides a general overview of this vehicle: its external and internal layout. It also includes a brief description of the new NPS AUV.

B. THE NPS AUV PHOENIX

Research on Autonomous Underwater Vehicles has been an ongoing project at the NPS since 1987 through the Phœnix project. This vehicle is a student research testbed for shallow-water minefield mapping missions. The Phœnix is also intended to demonstrate that there are no fundamental technical impediments to perform this kind of task using affordable underwater robots. Its design has to be robust and it must be low cost to be widely effective.

The description of the Phœnix architecture can be divided into two parts: the hardware and the software.

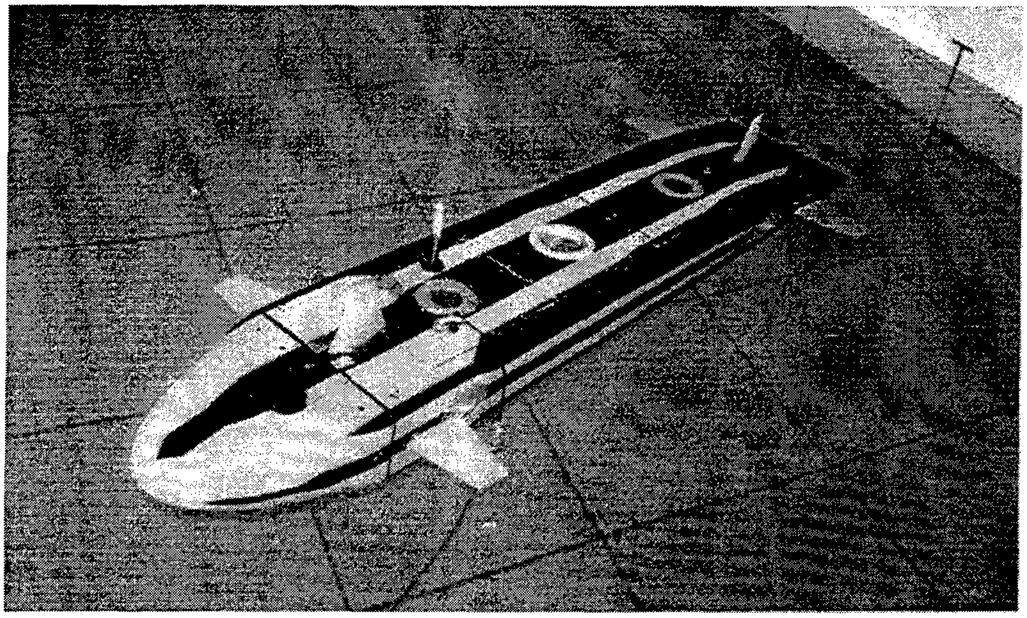


Figure II.1: Phœnix AUV undergoing testing at the Center for AUV Research (CAUVR) laboratory test tank in early 1995.

1. Hardware

The Phœnix is a complex robot, which contains various motors, controllers, servo-amplifiers and computer in a watertight hull. The external view of the hardware layout is shown below in the Figure II.2 .

The AUV is approximately 2.4 meter long, 0.46 meter wide and 0.31 meter deep. It has a 2 psi pressurized aluminum hull with a free-flooding nose cone that houses the AUV's acoustic measurement devices. The vehicle is designed to be neutrally buoyant at 387 pounds with a designed depth at twenty feet. It can be launched either from shore or from a boat. Lead acid batteries providing endurance up to two hours electrically power the submarine.

Two computers provide the control of the devices. These two computers can easily communicate together via an internal Ethernet network. The Ethernet can provide Internet connectivity to the boat through a tether. This tether can be used to monitor each process, collect data, or to intervene when an operational fault occurs. Ordinarily the tether is only used when the AUV is being tested ashore, or downloading test data at sea.

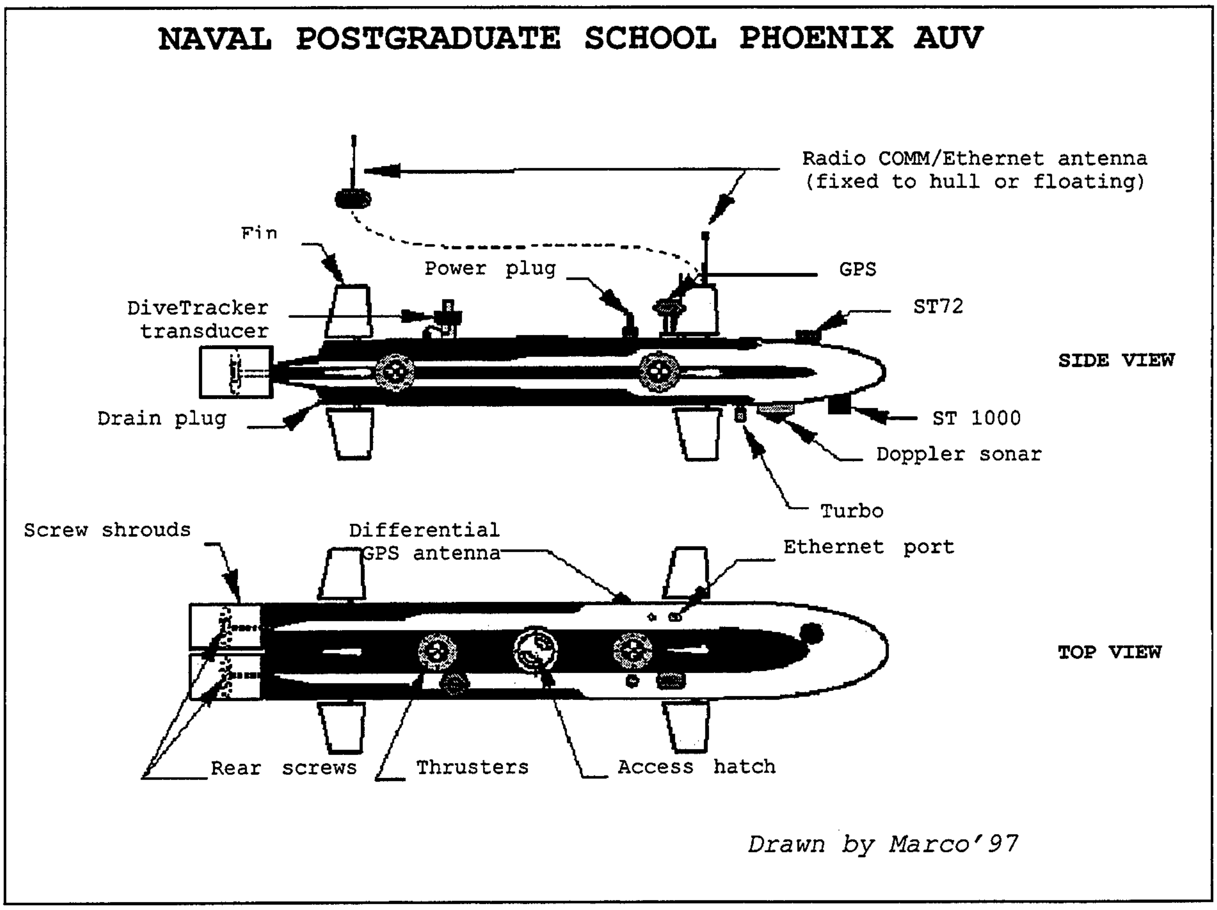


Figure II.2: AUV Phœnix external view.

For the survey and mine countermeasure purposes mentioned above, several devices have been installed in the AUV. Some are intended for the navigation and other are used for measurements. The following list details the primary pieces of hardware and their purposes:

- Four sonars:
  - Sontek ADV for water particle relative velocities (u,v,w)
  - RDI Doppler sonar for the speed over the ground,
  - Obstacle detection (ST 725 model),
  - Obstacle classification (ST 1000 model),
- Dive Tracker short baseline sonar navigation for precision tracking (not used at present),
- System Donner, solid state IMU, for sensing the vehicle's orientation by measuring angles and rates for roll, pitch and yaw respectively,

- A pressure-sensitive depth cell,
- A TCM2 electromagnetic compass

2. Software

The Phœnix AUV has used a tri-level software architecture called the Rational Behavior Model (RBM). RBM divides responsibilities into areas of open-ended strategic planning, soft-real-time tactical analysis, and hard real time execution level control. The RBM architecture has been created as a model of a manned submarine operational structure. The correspondence between the three levels and a submarine crew is shown in the Figure II.3.

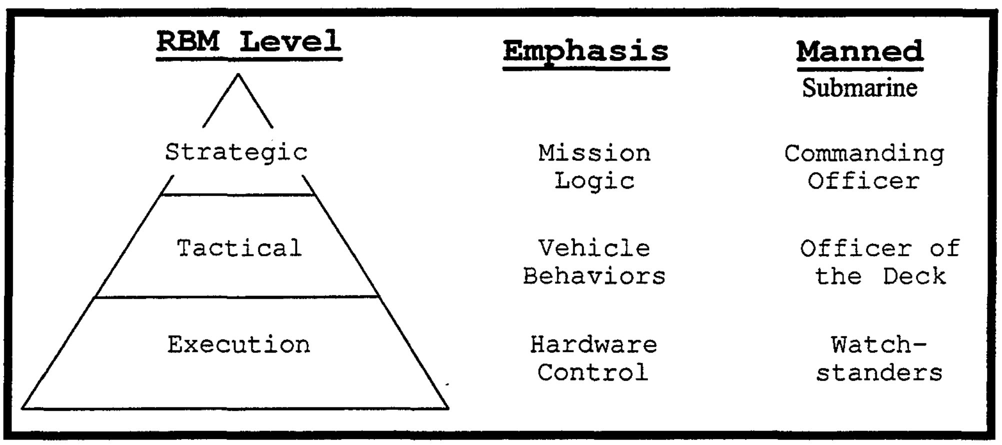


Figure II.3: The Relational Behavior Model tri-level architecture hierarchy with level emphasis and submarine equivalent listed [Holden 95].

The **Execution Level** assures the interface between hardware and software. Its tasks are to provide the motion stability of the vehicle, to control the individual devices, and to provide data to the tactical level.

The **Tactical Level** provides a software level that interfaces with both the Execution level and the Strategic level. Its chores are to give to the Strategic level indications of vehicle state, completed tasks and execution level commands. The Tactical level selects the tasks needed to reach the goal imposed by the Strategic level. It operates in terms of discrete events.

The **Strategic Level** controls the completion of the mission goals. The mission specifications are inside this level.

C. DESIGN OF THE NEW BOAT

During its planned missions like bottom surveying or mine hunting, the AUV needs to have the ability to take and keep its position in a dynamic environment relative to a local stationary object. This ability, through the use of sensors and actuators (propellers, fins, thrusters, etc.) consumes power. Thus power capacity is very important in an AUV because it will determine the duration of the mission. In order to increase the range of the boat, a new NPS AUV is being manufactured.

This new boat is very similar to Phœnix. Actually the global shape for both hardware and software has been maintained. The main differences stand in the addition of two ballast chambers (lengthening the hull) and the increase of the power capacity. The new vehicle will use a 48 volt batteries pack instead of a 24 volt batteries pack. The goal of the ballast chamber is to enable the AUV to sit on the ocean's bottom in a mechanical way (making it heavier) without consuming a lot of power.

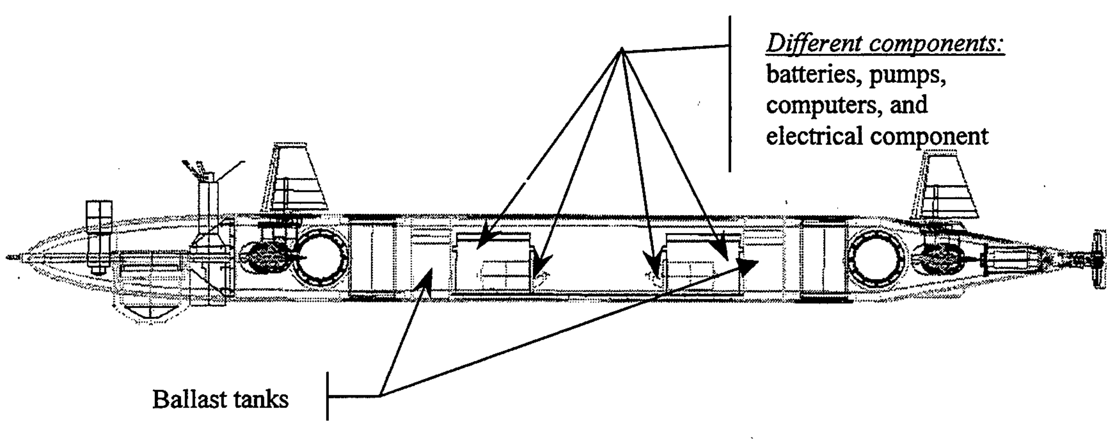


Figure II.4: New NPS AUV side view [Garibal 1999].

Furthermore, two Pentium processors are planned to be used to provide tactical, strategic and execution level control. They are faster and use less power than the Gespac combined to a Pentium chip used on the Phœnix AUV.

D. SUMMARY

The Phœnix AUV is a high technology Autonomous Underwater Vehicle (AUV) that can operate in shallow water. Using a tri-level software architecture RBM model, it mimics a manned submarine operational structure. The new AUV, which will be finished in September, should permit to increase the time autonomy and performance by using a faster system.

III. PROBLEM STATEMENT

A. INTRODUCTION

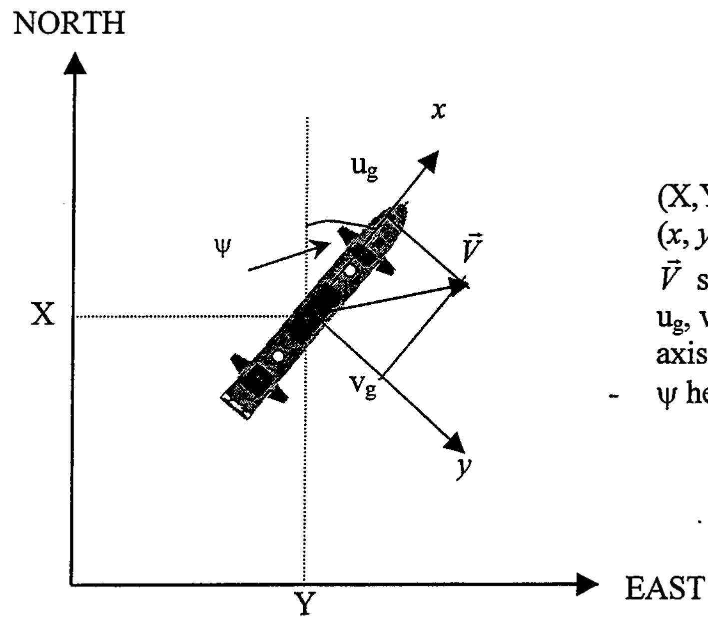
AUVs have a potential for use in many different applications. Many of these applications require highly accurate navigation. The gathered information is useful only if the AUV can be located precisely. When submerged, the location of the AUV can be determined using a wide variety of sensors such as gyroscope, compass or acoustic sensors. As accurate as they are, these sensors are nevertheless subject to drift. DGPS is highly accurate but these systems are unusable under water because of the severe signal attenuation and scattering. Fortunately, investigations have already shown that a combination of these two types of navigation can greatly reduce the position error.

The NPS AUV navigation uses sensor-based navigation. Thus, in order to improve the accuracy of the navigation it is worthwhile to add a DGPS. This report is focused on the integration of this system. Since there is no worldwide convention for the frequency of differential signal, the system must be easily alterable.

B. ESTIMATE THE POSITION

The estimate of the vehicle position when submerged is determined through a process called Dead Reckoning (DR). Position is calculated by integrating the velocity of the vehicle over time.

To do this calculation the reference system is chosen such as the X-axis points toward the North and the Y-axis correspond to the East.



(X,Y) Global reference's axis
(x, y) AUV reference's axis
$\vec{V}$ speed over the ground,
u_g, v_g its projection on the x and y axis respectively,
- ψ heading angle.

Figure III.1: AUV position nomenclature.

Thus the velocity equations are:

$$\dot{X} = u_g \cos\psi - v_g \sin\psi$$
$$\dot{Y} = u_g \sin\psi + v_g \cos\psi$$

By integrating these equations, the estimate of the position is:

$$\hat{X}(t) = \int \dot{X}(t)dt + X(0)$$
$$\hat{Y}(t) = \int \dot{Y}(t)dt + Y(0)$$

The onboard motion sensors provide heading and velocity measurements. For the NPS AUV, the velocity over the ground is determined using a Doppler sonar. On the new vehicle a compass will measure the heading whereas it was the estimate of a gyroscope and a compass measure on Phœnix.

Experiments carried out using the Florida Atlantic University (FAU) Ocean Explorer (OEX) vehicle to study the effect of the compass bias on the navigation have shown that heading bias warp the position [4]. The speed bias increases the position error too. The error grows as a function of time. Between these two sources of errors, the speed bias is the smaller of the two (0.2%). The heading bias often exceeds 5 degrees for some vehicle

orientation. These experiments used the same compass as Phœnix has. So during a long mission the standard deviation is a consequential problem that has to be minimized.

C. DGPS FIXES

DGPS fixes are often used to bound error growth. To reach a point the AUV surface regularly to take a DGPS position. Even if DGPS systems are very accurate, the new position is not taken has a new initialization for the navigation because the variability of DGPS is not equal to zero. Thanks to a filter, the position is now a combination of the position obtained through the Dead Reckoning process and the DGPS position.

$$\hat{X} = w_{DR}\hat{X}_{DR} + w_{DGPS}\hat{X}_{DGPS}$$

Where w_{DR}, w_{DGPS} are coefficients relative to the standard deviations of $\hat{X}_{DR}$ and $\hat{X}_{DGPS}$ and, $w_{DR} + w_{DGPS} = 1$

Figure III.2 shows the decreasing of the position error each time a DGPS fixes occurs. These results have been recorded during the experiment using the OEX stated above.

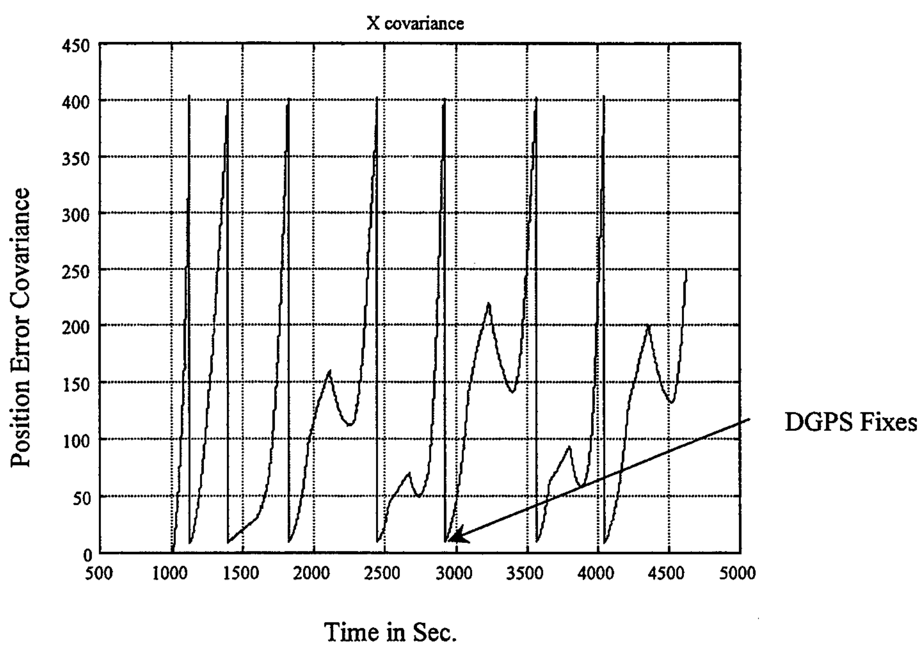


Figure III.2: Position error covariance vs time [4].

D. SUMMARY

To know precisely the position of the AUV is very important in order to use the data collected. Therefore the calculation of the position has been explained. Even though DGPS fixes are unavailable during fully submerged vehicle operations, the correction taken when surfacing reduce the position error due to sensors biases. This research presents the design of the DGPS system that will be mounted on the NPS AUV. As it is required to understand how the GPS works, a chapter is dedicated to it. This study also includes analysis of data collected from experimental testing to determine the performance of the system.

IV. GLOBAL POSITIONING SYSTEM (GPS) PRINCIPLES

A. INTRODUCTION

The Global Positioning System (GPS) is a satellite based global navigation system created and operated by the United States Department of Defense (DoD). Originally intended to enhance military defense capabilities, GPS capabilities have expanded for use by many civilian applications. GPS provides specially coded satellites signals that can be processed in a GPS receiver, enabling the receiver to compute position, velocity and time.

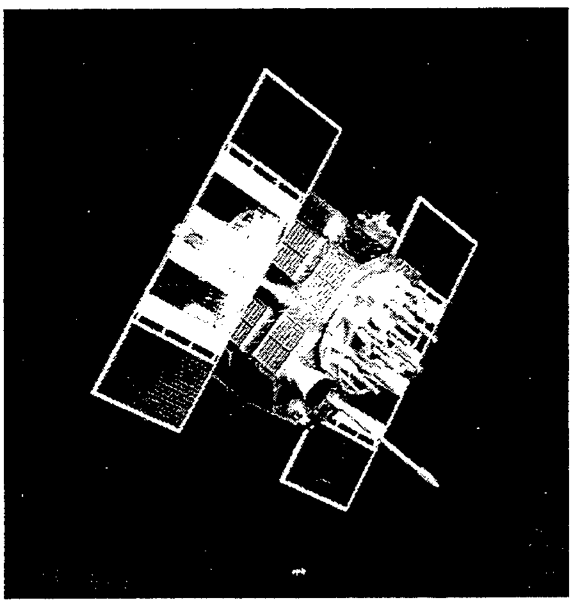


Figure IV.1: GPS Satellite [5].

B. GPS SETUP

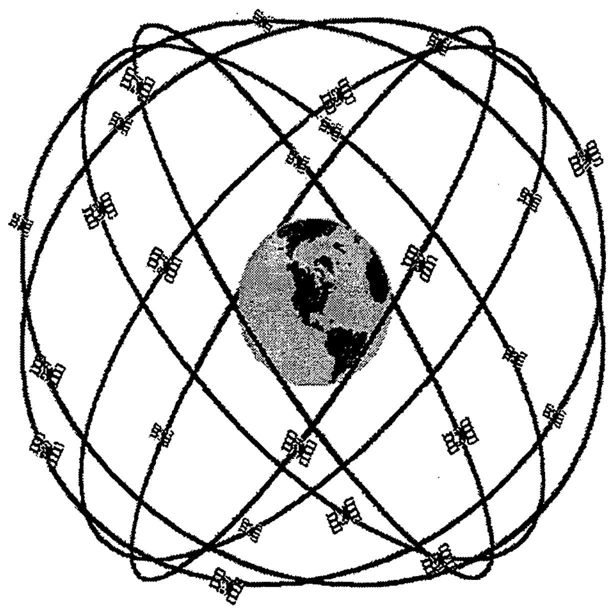
The GPS setup can be split in three segments:

- the space segment which includes the GPS signal transmission part,
- the control segment in charge of the survey of the space segment,
- the user segment.

1. The Space Segment

The Space Segment of the system consists of the GPS satellites. These space vehicles (SVs) send radio signals from space.

The nominal GPS Operational Constellation consists of 24 satellites that orbit the earth in 12 hours. There are often more than 24 operational satellites as new ones are launched to replace older satellites. The satellite orbits repeat almost the same ground track (as the earth turns beneath them) once each day. The orbit altitude is such that the satellites repeat the same track and configuration over any point approximately each 24 hours (4 minutes earlier each day). There are six orbital planes (with nominally four SVs in each), equally spaced (60 degrees apart), and inclined at about fifty-five degrees with respect to the equatorial plane. This constellation provides the user with between five and eight SVs visible from any point on the earth.



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

Figure IV.2: GPS Constellation [5].

2. The Control Segment

The Control Segment consists of a system of tracking stations located around the world.

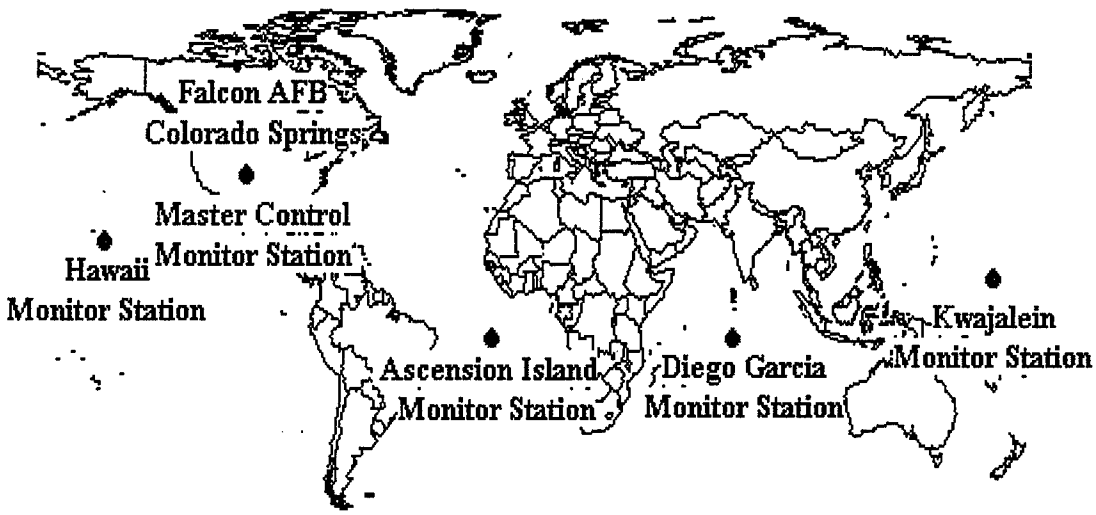


Figure IV.3: GPS master control and monitor station network [5].

The Master Control facility is located at Schriever Air Force Base (formerly Falcon AFB) in Colorado. These monitor stations measure signals from the SVs, which are incorporated into orbital models for each satellite. The models compute precise orbital data (ephemeris) and SV clock corrections for each satellite. The Master Control station uploads ephemeris and clock data to the SVs. The SVs then send subsets of the orbital ephemeris data to GPS receivers over radio signals.

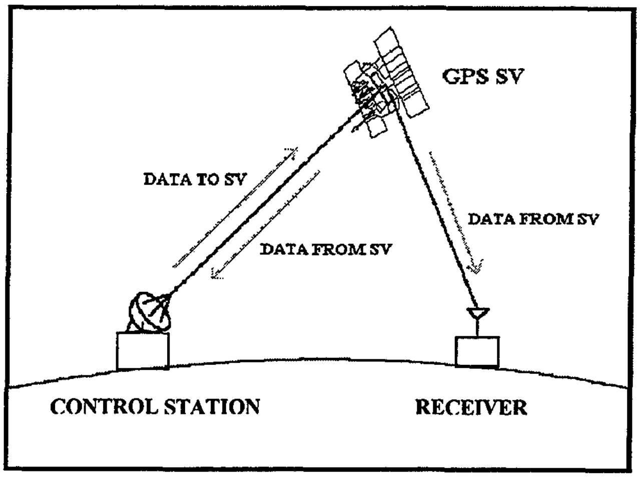


Figure IV.4: GPS control signal data path [5].

3. The User Segment

The GPS User Segment consists of GPS receivers and the user community. GPS receivers convert SV signals into position, velocity, and time estimates. GPS receivers are used for navigation, positioning, time dissemination, and other related research. Navigation receivers are made for aircraft, ships, ground vehicles, and for hand carrying by individuals. Time and frequency dissemination, based on the precise clocks on board the SVs and controlled by the monitor stations, is another use for GPS. Astronomical observatories, telecommunications facilities, and laboratory standards can be set to precise time signals or controlled to accurate frequencies by special purpose GPS receivers. Research projects have used GPS signals to measure atmospheric parameters.

C. GPS CODED SIGNALS

The positioning accuracy offered by GPS varies depending upon the type of service to which a user has access. For reasons of national security, GPS exists in two distinct forms: the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS).

Authorized users with cryptographic equipment and keys and specially equipped receivers use the Precise Positioning System. U. S. and Allied military, certain U. S.

Government agencies, and selected civil users specifically approved by the U. S. Government, can use the PPS.

U. S. Government provides the SPS free of charge worldwide to all civilians' users. The SPS accuracy is intentionally degraded by the DoD by the use of Selective Availability (SA) in order to prevent adversaries from exploiting highly accurate GPS signals and using them against the United States or its allies.

	Horizontal	Vertical	Time
SPS signal	100 m	156 m	340 nanosec
PPS signal	22 m	27.7 m	100 nanosec

Figure IV.5: SPS and PPS predictable accuracy [5].

The satellites transmit two microwave carrier signals. The L1 frequency (1575.42 MHz) carries the navigation message and the SPS code signals. The L2 frequency (1227.60 MHz) is used to measure the ionospheric delay by PPS equipped receivers. The SPS L1 code, called the Coarse Acquisition Code (C/A code), provides civilian receivers with distance measurements between the receiver's antenna and the GPS satellites in view of the antenna. The navigation message transmitted like this is a 50 Hz signal consisting of data bits that describe the GPS satellite orbits, clock corrections, and other system parameters.

D. GPS USES TRIANGULATION TO DETERMINE THE POSITION

Four GPS satellite signals are needed in order to a receiver to compute position in three dimensions and the time offset in the receiver clock.

The distance between the receiver and the satellite is basically calculated by multiplying the speed of the travelling signal with the amount of time it took to reach the receiver from the satellite.

Distance = Velocity * Time

The velocity in this case is roughly the speed of the light, or 186,000 miles per second in a vacuum.

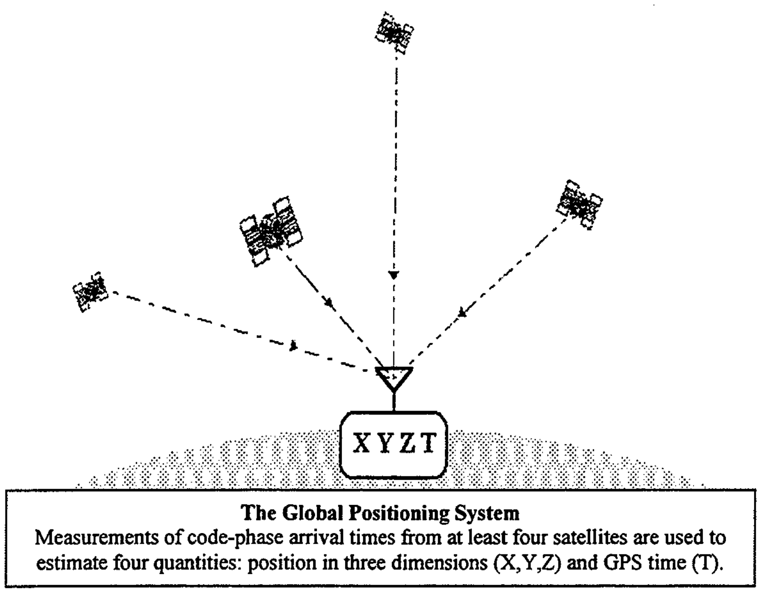


Figure IV.6: GPS uses four satellites to estimate position [5].

Since the receiver knows its distance and has an orbital map data, or ephemeris, of each satellite, it can use this information to plot a radius, with the satellite as the center. Using the same method for three satellites, the receiver can find a point that intersects with all three spheres. The intersection of these spheres gives two points but one of the two is a ridiculous answer and can be rejected without a fourth measurement. This point is the receiver's location and is usually updated at least once every second, depending on the receiver model. The fourth measurement is done as a crosscheck. If everything were perfect then all four satellite ranges would intersect at a single point. With imperfect clocks, the fourth measurement will not intersect with the first three. With that fourth measurement, the receiver calculates a correction factor that allows all the measurements to intersect at a single point since. Once the time correction has been applied, the position is known precisely.

E. GPS ERROR SOURCES

Errors can occur from several different sources. Some due to the physics involved in signal transmission and the Earth, while others are intentionally provided. The following list details the three important error sources.

- **Selective Availability (SA)**

SA is the intentional degradation of the SPS signals by a time varying bias. SA is controlled by the DoD to limit accuracy for non-U. S. Military and government users. The potential accuracy using the C/A code of around 100 meters is reduced using PPS to 30 meters. The SA bias on each satellite signal is different, and so the resulting position solution is a function of the combined SA bias from each satellite used in the navigation solution. Because SA is a changing bias with a long time constant, position solutions or individual satellite pseudo-ranges can not be effectively averaged over periods shorter than a few hours. Differential corrections can cancel common mode errors but must be updated with delays less than the correlation time of SA (and other bias errors).

- **Atmospheric errors**

The satellite's signal may bounce off particles in the atmosphere, which creates a slight time delay to the receiver. Since the receiver is comparing the time stamp provided by the satellite with its own record of time, any slight delays will add an error to the triangulation result. Signals may also bounce off of buildings, mountains, and other imposing objects before reaching the receiver, increasing the amount of travel time. This is called Multipath reception. Multipath problems are difficult to detect, sometimes hard to avoid and compensate.

- **Geometric Dilution of Precision (GDOP)**

GPS ranging errors are magnified by the range vector differences between the receiver and the satellites. The volume of the shape described by the unit-vectors from the receiver to the satellites used in a position fix is inversely proportional to GDOP. Poor GDOP, a large value representing a small unit vector-volume, results when angles from receiver to the set of satellites used are similar. Good GDOP, a small value representing a large unit-vector-volume, results when angles from receiver to satellites are different.

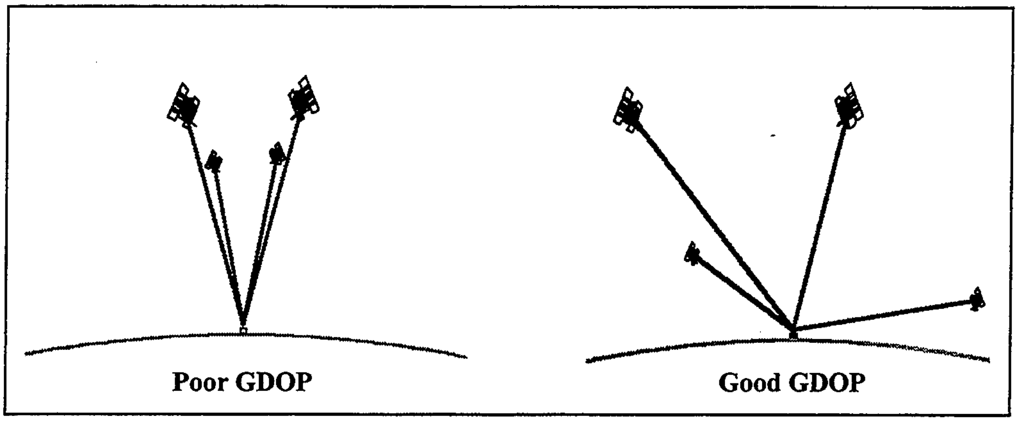


Figure IV.7: Geometric Dilution of Precision (GDOP) [5].

F. DIFFERENTIAL GLOBAL POSITIONING SYSTEM (DGPS)

The cumulative errors described above can be reduced through a technique known as Differential GPS (DGPS). This approach involves the cooperation of two receivers: one is stationary (reference station whose location is known) and the other can be mobile in the surrounding region making position measurements.

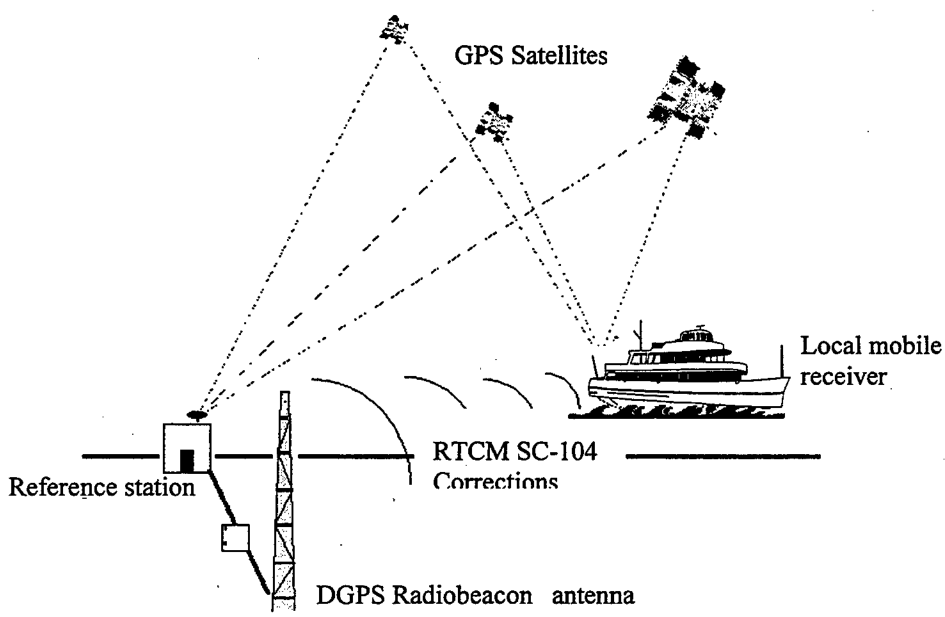


Figure IV.8: Differential Global Positioning System (DGPS) [6].

GPS satellites are so far out in space that the distance between the two local receivers relative to satellite distance is insignificant. So if two receivers are close to each other (a few hundred kilometers), the signals that reach both of them will have traveled through virtually the same slice of atmosphere, and so will have virtually the same errors. Because the local reference station is fixed at a known position, satellite signal errors can be calculated. These local errors can then be communicated via radio to local mobile receivers.

To determine the errors in the satellite signals, the receiver (reference station) measures the ranges to each satellite using the signal received and comparing these measured to the actual ranges calculated from its known position. The difference between the measured and calculated range is the total error. The error data for each tracked satellite is formatted into a correction message and transmitted to GPS user. The differential corrections are then applied to the GPS calculations in the mobile station, thus removing most of the satellite signal error and improving accuracy.

G. DGPS FORMAT

The governing standard associated with GPS is the Interface Control Document, ICD-GPS-200, maintained by the U. S. DoD. This document provides the message and signal structure information required to access GPS.

Like GPS, DGPS broadcast standards have been established to ensure compatibility between DGPS network, and their associated hardware and software. The Radio Technical Commission for Maritime Services Special Committee 104 (address given in Appendix C) has developed the primary DGPS standard in use today designated RTCM SC-104 V2.2.

The RTCM data comprises 16 messages to correct raw GPS positions. A DGPS beacon will broadcast either Type 1 or Type 9 messages, both of which contain similar information. These two messages contain corrections to each GPS satellite. The Type 3 message contains the beacon's reference station position, often accurate to within centimeters. The Type 6 message contains null information, and is broadcast so that a beacon receiver demodulating the data from the broadcast does not lose lock when the

beacon station has no new data to transmit. The RTCM SC-104 message contains no provision for transmission or reception of receiver control and status information. To implement these functions, most of the DGPS receivers are capable of processing a subset of standard NMEA 0183 messages.

NMEA 0183 is a communication standard established by the marine industry. It has found use in a variety of marine electronics devices, including ship-borne radar systems. The National Marine Electronics Association has developed a significant number of messages specifically for use with GPS. This association publishes updates to the NMEA 0183 standard. A few samples of messages are available in Appendix C.

H. SUMMARY

The Global Positioning System is a satellite-based navigation system created by the United States DoD. The GPS receiver needs at least four satellites to compute position by triangulation. The system is free and available all around the world. Due to the Selective Availability, the atmospheric conditions and the geometric dilution of precision, a regular GPS is not very accurate: the position is given in a range of 100m. A more accurate position can be obtained using a Differential GPS.

V. NPS AUV DGPS SYSTEM DESIGN

A. INTRODUCTION

A DGPS can be built in many different ways with the products manufactured. On an AUV, the drag, the overall dimensions and missions requirements are important concerns to choose the components of the DGPS. In this chapter, the constraints to design the DGPS are explained. The principles of the chosen DGPS are then presented. It also includes a description of the DGPS equipments.

B. DESIGN DESCRIPTION

1. Constraints

The DGPS has been adjusted to intensify the accuracy of the GPS. Unlike it, the DGPS frequency is not standardized yet. To use differential corrections, the first thing to know is the frequency range and the coverage of the signal that is going to be tuned.

There are two differential signals available in Monterey. One is the property of Monterey Bay Aquarium Institute (MBARI) and the other one belongs to the U. S. CoastGuards (USCG). The correction from MBARI repeated through Mount Toro is transmitted at 466.7625 MHz and covers the Monterey Bay region. The USCG signal is sent from Pigeon Point (situated North of Santa-Cruz) at 287 kHz. The advantage of that signal is that it is not limited to Monterey Bay. A network of antennas located along the U. S. coast, the Great Lakes and the Inland Rivers provide a wide differential correction area between 283.5 and 325 kHz.

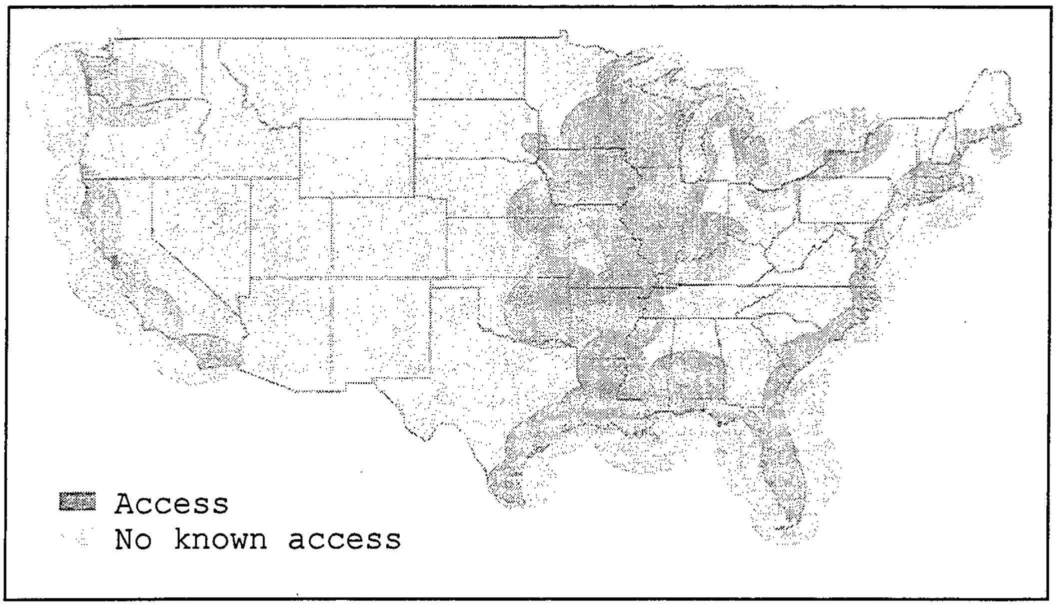


Figure V.1: Area of the United States with access to USCG differential correction [Figure constructed from data given in www.navcen.uscg.mil/dgps].

Once the frequency is determined, the chosen beacon is dedicated to the frequency coverage. The beacon becomes useless if situated outside of the limits. This induces another problem for the system that is going to be installed on the NPS AUV. Indeed, NPS AUV missions are planned to take outside Monterey Bay in the Gulf of Mexico for example. Missions along the Portuguese coast are also expected. A differential beacon receiver able to tune to the USCG correction is worthwhile. DGPS receivers adapted to each area or country frequency are manufactured. That requires the ability to change the differential beacon receiver for every work area/location. On an underwater vehicle this task is not so simple. As each differential receiver has is own shape and size, adequate free space needs to be dedicated and an adjustable mounting must be designed. Moreover, personnel access to the DGPS needs to be easy.

To put it briefly, replacing the differential beacon on an AUV in order to receive GPS correction all around the world is possible but not practical. Therefore, in this study an easily alterable system and one that can overcome the problems induced by the non-standardization of the differential frequency is presented.

Frequencies in use for differential correction publication are relatively low compared to L1 and L2, meaning that an AUV mounted system would have a large antenna and large attendant drag. The design presented here overviews these problems and uses only two antennas on the AUV; one for radio control/differential correction reception, and a GPS antenna.

2. System Explanation

The DGPS suggested in this study is a system where the differential beacon receiver has no physical tether with the GPS receiver.

Numerous products manufacture differential beacon receiver and GPS receiver in the same device. The RTCM SC-104 formatted message is transmitted to the GPS board through an RS-232 serial port as shown in figure V.2.

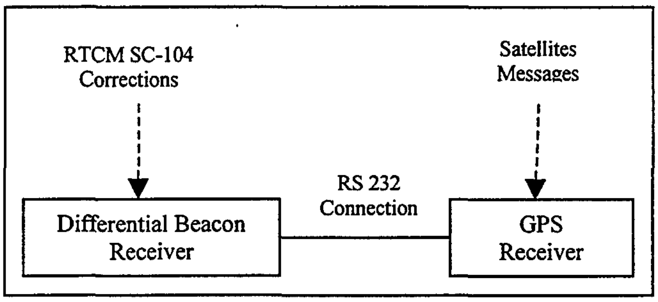


Figure V.2: Regular DGPS unit.

The RS 232 link is cut. The transmission of the correction will be established via radio communication using a 900 MHz spread spectrum radio modem (called Freewave, name of the manufacturer).

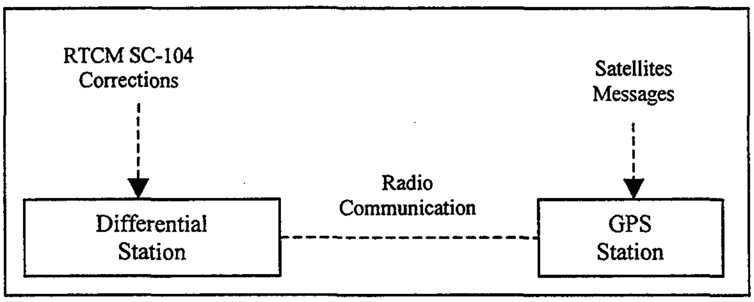


Figure V.3: Our DGPS design.

The differential beacon receiver here is separated from the GPS receiver. Thus, it can be located everywhere, on a ship's deck or on a wharf for example. The only constraint is that it needs to be in radio communication receiver range of the AUV. That means inside a circle with at least a 4 miles radius and the AUV as center.

With this design, the differential station can be moved/removed without any modification to add on the DGPS hardware inside the AUV.

Using a single 900 MHz antenna on the AUV for the reception of both DGPS corrections and control signals reduces the onboard aerials to two.

C. HARDWARE

The hardware design chosen to accomplished the system stated above are described below. One of the concerns in choosing hardware was the price since one of the interests of the AUV project is to build a low cost vehicle. Another concern was the size of the devices especially for the hardware mounted on the AUV. The differential station has to be portable too.

The technical specification for each device is provided in Appendix B.

1. Differential Station

The differential station is composed of two devices linked together through an RS 232 serial port. The first component is the DGPS receiver to pick up the GPS correction and the second is the freewave modem that enables the correction to be sending to the AUV.

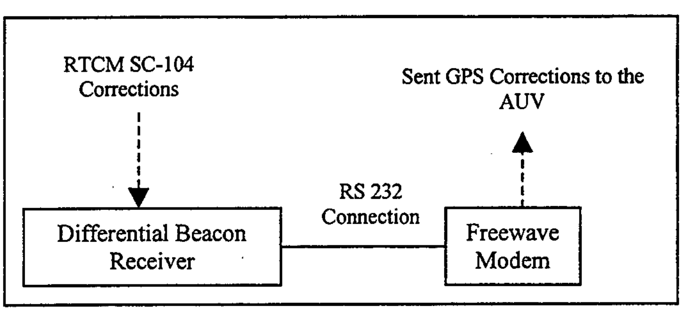


Figure V.4: Differential station design.

a. The Receiver

The CSI ABX-3, shown in Figure V.5, obtains differential GPS corrections broadcast from radiobeacons adhering to the standard RTCM SC-104 format and operates in the frequency range of 283.5 to 325 kHz (USCG frequency range). It is designed for hands-free operation. However a manually tune mode is available and responds to standard NMEA 0183 command messages and status queries. These commands are given in Appendix B.

For hands-free operation, the Automatic Beacon Search (ABS) selects and tunes to the most appropriate beacon without operator intervention. Two independent channels are used to identify and lock to DGPS beacons without interrupting the continuous flow of data to the GPS receiver. The primary channel automatically locks to the station providing the highest quality signal while the second channel continues searching for superior beacon signals. If DGPS broadcast is identified that exhibits a 2db greater Signal Strength (SS) over that of the primary station, the receiver will automatically switch to this beacon.

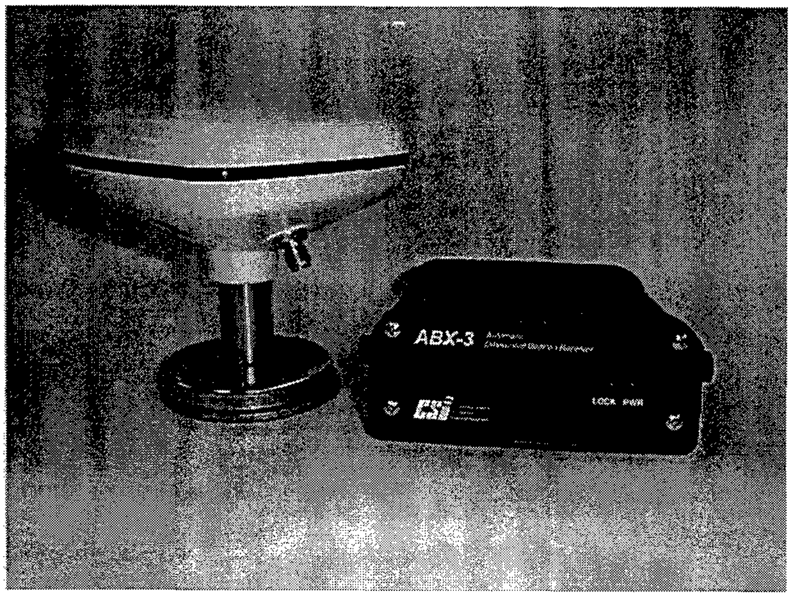


Figure V.5: The ABX-3 receiver and the MBL-3 antenna.

On the front panel a red and a green LED indicate receiver power and lock status respectively. This device receive 9-40 VDC from an external power source. The antenna, shown on Figure V.5, is a CSI MBL-3 magnetic field antenna. It is an H-field beacon loop antenna. H-field antennas are less susceptible than a conventional whip antenna to predominate noise, including precipitation noise and do not require ground connection.

b. The Freewave Modem

The Freewave wireless data transceivers, shown in Figure V.6, always work in pairs. Here one is linked to the differential receiver and the other one to the GPS receiver.

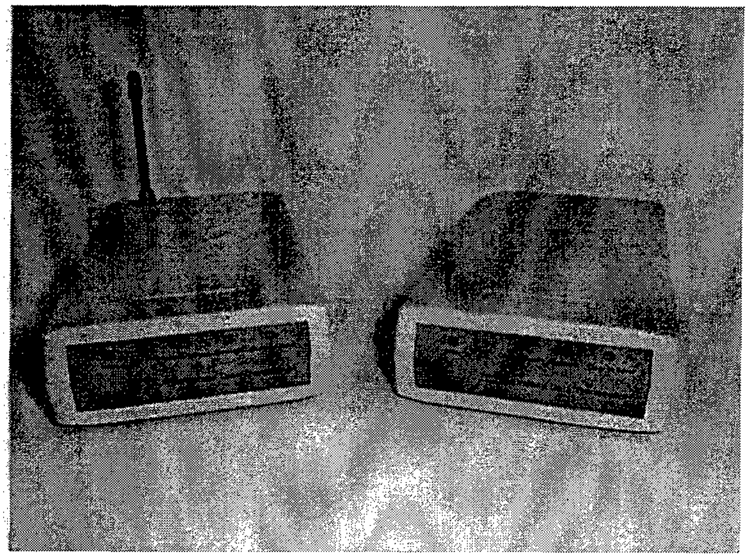


Figure V.6: The Freewave wireless data transceivers and their antenna.

Depending on the pair of transceivers used the power is 12 Vdc or 24 Vdc. To establish communication between them, the baud rate has to be set on each modem through configuration software to match the baud rate of the instrument to which it is attached (9600 for both GPS and DGPS receiver).

These modems are preset on the same channel to communicate only with each other. The most common and straightforward link is a master communicating to a

slave in a dedicated link, which is a point-to-point application. The messages are sent in packet whose size depends of the setting. A checksum is included to each packet to check if the message has not been damaged during the transport. If an error occurs, the message has not been transmitted correctly. The packet is then rejected and not transmitted to the GPS receiver.

Placement of the Freewave unit is likely to have significant impact on its performance. In general rules, the higher the antenna for the transmission is placed above ground the better the communication link [Communication with Clayton Jones, Webb Research Institue].

2. GPS Station

This part of the system is composed of a GPS receiver, one of the freewave modem stated above and an antenna for each of them to receive satellite messages and GPS correction respectively.

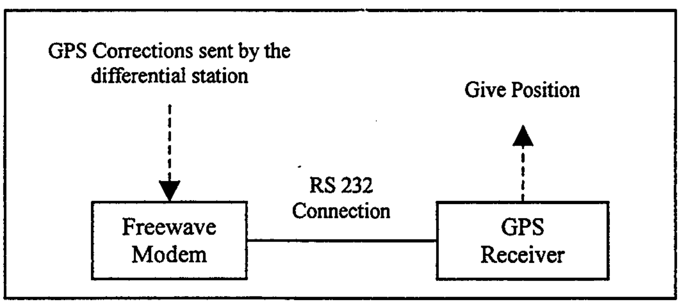


Figure V.7: GPS station design.

Since the freewave transceiver has already been described, this paragraph is focused on the description of the GPS receiver.

The GPS receiver is a Motorola VP Oncore Receiver. This receiver, shown in FigureV.8, is an 8 channels parallel design capable of tracking 8 satellites simultaneously. It provides position, velocity and time information over a serial RS 232 port in a format called Motorola Binary Format. This format is explained in the next chapter. A converter integrated to the system provides the 5Vdc required for the GPS receiver from an external power supply between 9-40Vdc.

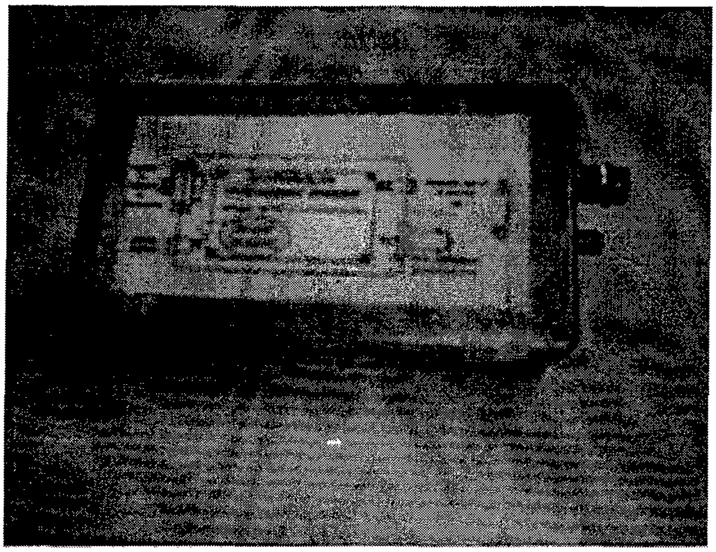


Figure V.8: Motorola Oncore Receiver.

Once the receiver is tracking three or more satellites, position computation is done automatically. When a differential correction is received, The GPS receiver remains it until an update correction is accomplished. After a few minutes (2-3 min.), if no updated corrections is available, the GPs receiver stops using differential correction to compute position and become a regular GPS. Without SA on and without differential corrections, the receiver can provide 25m position accuracy. With SA on, the position is degraded to 100m accuracy and with differential correction the accuracy range is 1-5m.

In this study, two GPS antennae have been tested but only one is used for the results. One is the Motorola GPS Antenna and the other one is the Micropulse 18800 antenna, which is not a preamplified antenna unlike the Motorola Antenna. This last antenna was very convenient because of its size. However after a few tests, the antenna proved to be inefficient. Six or seven satellites have been tracked with the Motorola antenna whereas only three satellites tracked either because a preamplified antenna is required. This is why the chosen antenna to carry out the experiments is the Motorola antenna. The signal preamplification within the antenna is made possible by external power supplied by the GPS receiver to a Low Noise Amplifier (LNA) internal to the antenna.

E. SUMMARY

The non-standardization of the differential correction's frequency leads to the requirement that the differential receiver be easily alterable to match AUV mission requirements. The hardware described in this chapter composes a DGPS that separate the differential receiver from the GPS receiver. The differential receiver transmits the differential correction via radio modems to the GPS receiver aboard the AUV. An advantage of such design is that the differential receiver can be changed without any intervention on the AUV. Another advantage is that only one antenna is added on the AUV for the DGPS. The differential correction will be received by the AUV through the aerial used to send the control commands.

VI. OBTAINING POSITION INFORMATION FROM THE MOTOROLA GPS RECEIVER

A. INTRODUCTION

The Motorola GPS receiver uses a format created by the manufacturer to send the data to the user. This chapter provides a description of this format. Among the messages transmitted by the GPS receiver, only the message containing position information are needed for the study. Therefore, the composition of these messages is detailed. An explanation of the C-program written to translate the messages into a format understandable by the user is also includes.

B. MOTOROLA BINARY FORMAT

The binary data messages used by the Motorola Oncore receiver called Motorola Binary Format consists of a variable number of binary characters. These messages begin with the ASCII @@ characters and are terminated with the ASCII carriage return line feed <CR><LF>. The first two bytes after the @@ characters are two ASCII message ID bytes that identify the particular structure and format of the remaining binary data. The last three bytes of all messages contain a single byte checksum (the exclusive-or of all message bytes after the @@ and before checksum), and a message terminating ASCII carriage return line feed character sequence.

$$\underbrace{\text{(@@)}}_{\substack{\text{Message}\\ \text{Start}}}\quad \underbrace{\text{(A..Z)(a..z,A..A,0..9)}}_{\text{Message ID}}\quad \underbrace{\text{(.........................)}}_{\substack{\text{Binary Data Sequence:}\\ \text{Variable number of bytes of binary}\\ \text{data dependent on the message type}}}\quad \underbrace{\text{(C)}}_{\text{Checksum}}\quad \underbrace{\text{(<CR><LF>)}}_{\text{Message Terminator}}$$

Figure VI.1: Motorola Binary Format Messages skeleton.

Among the following list, which is a complete list of output message available, only the position message interests the study:

- Position/channel status
- Satellite range data output
- Pseudorange correction output
- Ephemeris data output
- Visible satellite status
- DOP table status
- Almanac status
- Almanac data output

C. FORMAT OF THE POSITION MESSAGE

The position message starts with @@Ea. This message is a 76 bytes length. It does not provide only the position by giving the latitude, the longitude and the altitude but it also includes date, velocity and channel status.

The composition of the message is as follow:

@@Eamdyyhmsffffaaaaoooohhhhmmmmvvhhddtntimsdimsdimsdimsdimsdimsd imsdimsdsC<CR><LF>

Date	
m – month	1 .. 12
d – day	1 .. 31
yy – year	1980 .. 2079
Time	
h – hours	0 .. 23
m – minutes	0 .. 59
s – seconds	0 .. 60
ffff – fractional sec	0 .. 999,999,999 (0.0 to 0.999999999)

Position	
aaaa – latitude in msec	-324,000,000 .. 324,000,000 (-90° to +90°)
oooo – longitude in msec	-648,000,000 .. 648,000,000 (-180° to +180°)
hhhh – height in cm (GPS, ref ellipsoid)	-100,000 .. +1,800,000
mmmm – height in cm (MSL ref)	-100,000 .. +1,800,000
Velocity	
vv – velocity in cm/sec (true north res 0.1°)	0 .. 51400 (0 to 514.00 m/sec)
hh – heading	0 .. 3599 (0.0 to 359.9 deg)
Geometry	
dd – current DOP (0.1 res)	0 .. 999 (0.0 to 99.9 DOP) (0 – not computable), or position-hold, or position prop
t – DOP type	0 – PDOP (in 3D) 1 – HDOP (in 2D)
Satellite visibility and tracking status	
n – number of visible satellite	0 .. 12
t – number of satellites	0 .. 8
For each of eight receiver channels	
i – satellite ID	0 .. 37
m – channel tracking mode	0 .. 8

0 - Code search
1 - Code Acquire
2 - AGC Set
3 - Freq Acquire
4 – Bit Sync Detect
5 - Message Sync Detect
6 - Satellite Time Avail
7 - Ephemeris Acquire
8 - Available for position

s – Signal Strength (number proportional to SNR)	0 .. 255

d – Channel Status flag

Each bit represents one of the following:

(msb) Bit 7: Using for position fix
Bit 6: Satellite Momentum Alert Flag
Bit 5: Satellite Anti-Spoof flag set
Bit 4: Satellite reported unhealthy
Bit 3: Satellite reported Inaccurate (>16 meters)
Bit 2: Spare
Bit 1: Spare
(lsb) Bit 0: Parity error

(end of channel dependent data)

s – receiver status message

(msb) Bit 7: Position propagate mode
Bit 6: Poor geometry (DOP>20)
Bit 5: 3D fix
Bit 4: Altitude hold (2D fix)
Bit 3: Acquiring satellites/Position hold
Bit 2: Differential
Bit 1: Insufficient visible satellites (<3)
(lsb) Bit 0: Bad almanac

C – Checksum

D. CODE TO TRANSCRIBE THE FORMATTED MESSAGE

The Motorola Binary formatted message is not meaningful for users. It is just a succession of ASCII characters. The C-code program in Appendix D transcribes the ASCII character into the variables described above, in a format understandable by every users. The units of these values are international units, i.e. meters and seconds. The bytes coming out from the serial port are read byte by byte. The control to stop the program is realized by a do-loop. The user inputs the number of loops at the beginning of the run: one loop correspond to one second.

1. Parse the Message

The first thing to do with these messages is to find the beginning and the end of each message. This task is realized by finding carriage return line field characters. Each time the code read a byte from the serial port, it compares this value with the hexadecimal code for carriage return. If a carriage return <CR> is found, the following byte is exanimate else the reading of the bytes continues until another <CR> is detected. When a line field is recognized after a carriage return, the end of the message and the beginning of the next message is figured out. An array of characters called "mem" record each byte that is read from the buffer.

The code for this parsing is:

```
read(fid,x_buff,1);
New_message= FALSE;
NOT_CR= TRUE;
while (New_message == FALSE)
{
   if (x_buff[0] == CR)
   {
      mem[0]= x_buff[0];
      read(fid,x_buff,1);
      if (x_buff[0] == LF)
      {
         New_message = TRUE;
      }
      else
      {
         mess[cpt]= mem[0];
         cpt=cpt+1;
         NOT_CR= FALSE;
      }
   }
```

```
        if (New_message == FALSE)
        {
            if (NOT_CR)
            {
                mess[cpt]=x_buff[0];
                cpt=cpt+1;
                read(fid,x_buff,1);
            }
            else
            {
                NOT_CR=TRUE;
            }
        }
    }
```

2. Check for a Position Message

The all type of messages stated above in section A are send by the GPS. Only the messages containing position information are interesting. So, the next step of the program is to keep only this type of message.

Once the parsing is achieved, a control on the first four bytes of the recorded message is realized. If these bytes correspond to @@Ea, then it is a message as required. The transcription phase can start. Else a new loop is activated and the reading of the next message begins.

The lines below show the C-code to achieve that step.

```
pos_control = TRUE;
        k=0;

        position_mess[0]= 0x40;
        position_mess[1]= 0x40;
        position_mess[2]= 0x45;
        position_mess[3]= 0x61;

        while (pos_control & k<4)
        {
            pos_control= (mess[k] == position_mess[k]);
            k= k+1;
        }
```

3. Transcription of the Message

The transcription of the message is quite simple because all the bytes are memorized in an array. So the only thing to do is to pick up the element of the array corresponding to the variables needed. For example, if we want to know the month, the Motorola Binary format indicates that the fifth character from the beginning of the message is dedicated to code this information. In the array this character is placed in the element mem[4] (the index of an array starts at 0). To get this value, we just have to print it as a decimal character on a screen or on a file, depending on the future use of the variable.

Example of code:

```
month[0] = mess[4];
printf("%d",month[0]);
```

Other informations are less simple to obtain because it can be coded with two or four bytes. That means two or four elements of the array correspond to one value, which is the case for the latitude or the year. Sometimes, only a bit gives the information like for differential or not.

Using a pointer solves the first case. The pointer is a character type variable that points the address dedicated for the value of year for example. Each byte of the variable 'year' is then affected of the array's element corresponding, mem[6] and mem[7]. This is depicted below:

```
x = &year;          /* x points to the address of year */
x[0] = mess[7];     /* year is an unsigned short variable*/
x[1] = mess[6];     /*(2 bytes) */
```

A multiplication to mask some bits is applied to solve the second case (one bit codes an information). This multiplication consists of multiplying the bits that we want to mask by 0 and the bits we want to isolate by 1. The Figure VI.2 explains the principle of that operation.

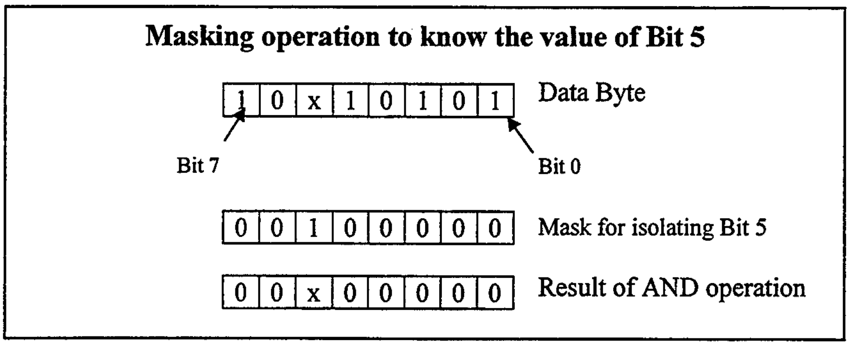


Figure VI.2: Mask operation to isolate a bit.

This technique is used to know if the GPS used differential corrections or not. This information is contained in the third bit of the element mem[72]. So the multiplication of that elements by the hexadecimal value '04' will be equal either to '00' or '04'. If '04' is obtained, the GPS uses differential correction to compute the position.

This task is express in the code by:

```
diff[0] = mess[72] & 0x04;
if (diff[0] == 0x04)
         {
            printf("Differential signal\n");
         }
         else
         {
            printf("Not differential signal\n\n\n");
         }
```

All information provided by the message and useful for the study are obtained using the appropriate technique among the three technique stated above.

4. The Output

The transcribed information are then print on a screen for a direct visualization of the collected data and on files to be able to plot and discuss them.

FigureVI.3 shows a screen that can be seen running the code described before.

Latitude in milliseconds

```
Date: 7/21/1999
Time: 18h 23min 9.752133sec

Number of visible satellites:6
Number of satellites tracked:5
Dilution of precision: 3 HDOP

Latitude: 131722907     36^35'22''907
Longitude: -438707066    -121^51'47"66
Height (GPS): 8.000000 (m)

          Differential signal

Channel     ID     Mode     SS     Used
   1         6       8      41      1
   2        17       8      40      1
   3        21       0      61      0
   4        22       8      33      1
   5        23       8      30      1
   6        26       8      26      1
   7         0       0       0      0
   8         0       0       0      0
```

Latitude in degrees, minutes, seconds, milliseconds.

Figure VI.3: Example of screen output obtained running the C-code.

F. SUMMARY

The format used by the GPS receiver to transmit the data to the user has been explained in this chapter. The composition of the position messages has been detailed, since only this kind of message is required for the study. The C-program written to extract the interesting messages and the different information that they contain has also been explained.

VII. EXPERIMENTAL RESULTS

A. INTRODUTION

The results presented in this chapter come from testing made on the parking of the AUV research lab. This is not ideal conditions nor conditions that can be found on the ocean because of the trees and the building that oppose the signal and create multipath. The equipment described in chapter IV was installed on two carts, one for each station. This setup enables the experiment to simulate the AUV mission when surfacing, as well as the distance between the AUV and the location of the differential station.

Two types of tests have been carried out: static tests and dynamic tests.

B. STATIC TESTS

A test was performed to compare the position's variability of a GPS with or without differential correction.

Without differential correction, the latitude absolute error is in a range of 40m, as shown in Figure VII.1. The same position error is observed for the longitude (Figure VII.2) whereas less than 5m latitude and longitude accuracy is obtained with the same GPS receiving differential correction.

This result is depicted in Figures VII.3 and VII.4. Notice that the quality of the satellite constellation does not influence this result. The same number of satellites is used to compute the position for both GPS with or without correction.

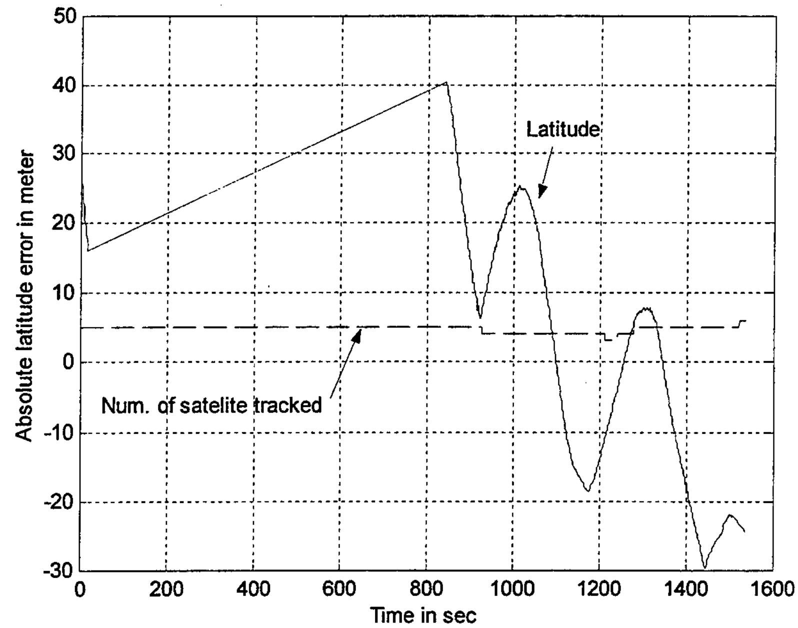


Figure VII.1: Absolute latitude error vs time without differential correction.

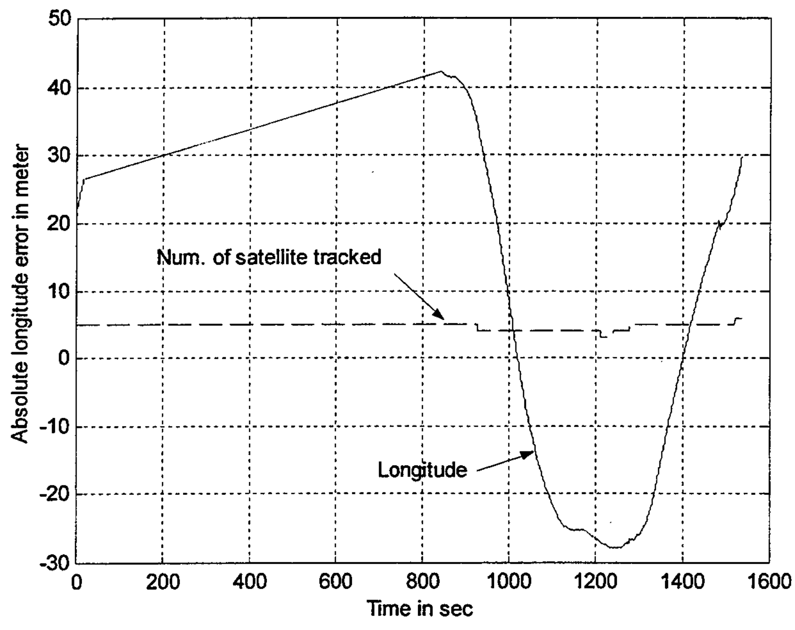


Figure VII.2: Absolute longitude error vs time without differential correction.

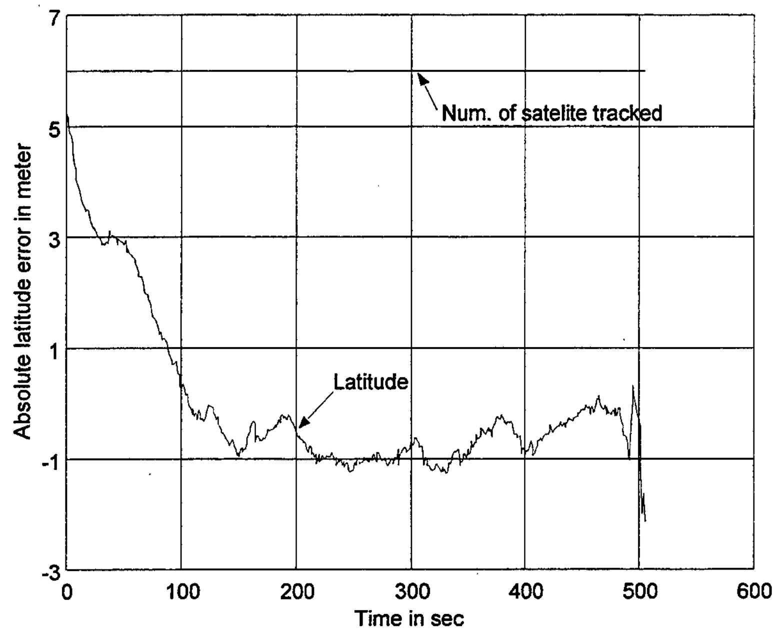


Figure VII.3: Absolute latitude error vs time with differential correction.

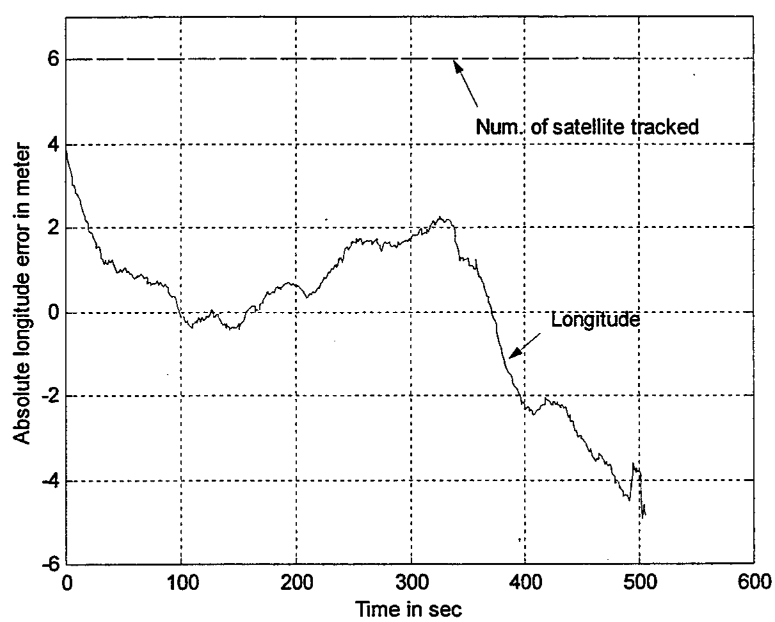


Figure VII.4: Absolute longitude error vs time with differential correction.

The next test is to determine if the transmission of the differential correction through the Freewave modem affects the accuracy of the DGPS. Therefore, three data sets are recorded successively. The only change in the setup is the distance separating the Freewave antennas. For the first set, the Freewave modems are not used. The physical tether between the differential and the GPS receivers is rebuilt. About 23 and 40 feet separate the Freewave antennas in the second and third set.

Regarding the results plotted in Figure VII.5, no main difference is observed between these three data sets. The variability of the given position remains in a range of 5m in latitude and 3m in latitude but most of the value are in a square 2m high and 6m wide. Finally the accuracy found by the experiments matches the accuracy expected by by the Motorola GPS receiver's technology.

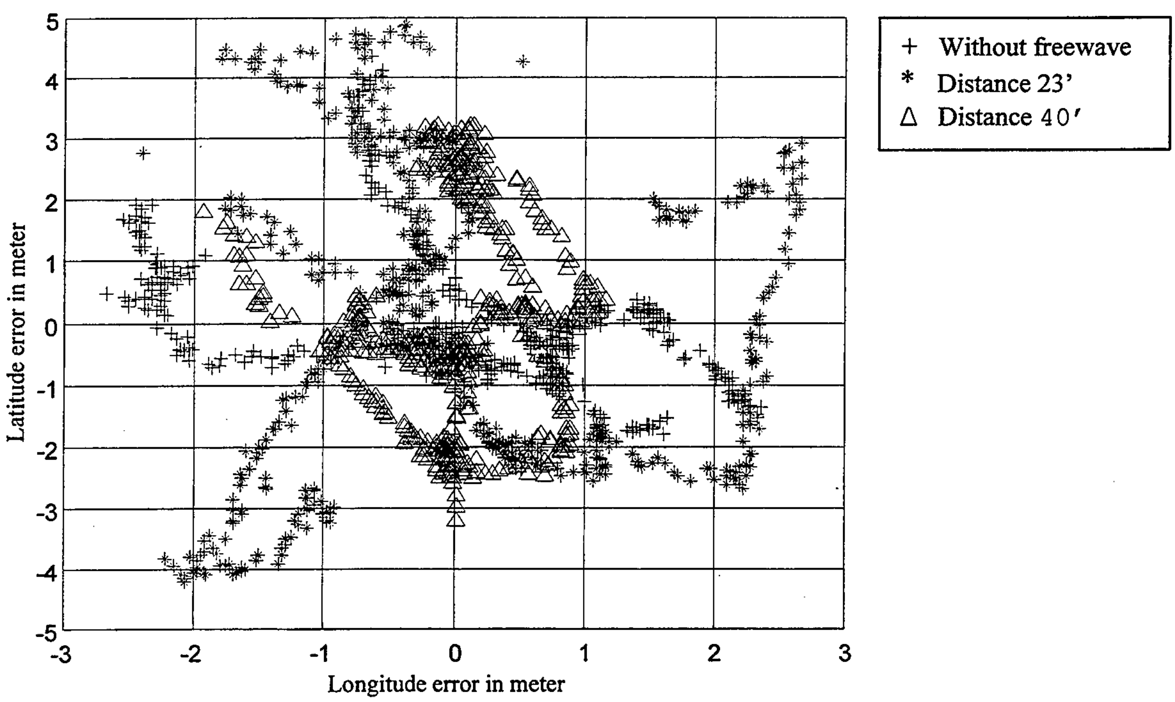


Figure VII.5: Position error without radio transmission and with the antennas far away from 23' and 40'.

The standard deviation defined by the equation below for these tests is resumed in the following table.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$ where N is the length of the data file

$\bar{x}$ is the mean of the data

	Latitude standard deviation	Longitude standard deviation
Without	1.08	1.27
Distance 23’	2.49	1.29
Distance 40’	1.67	0.57

Regarding these result, that the differential signal is received directly or through the Freewave modem does not affect the accuracy of the position: a standard deviation of 57cm is obtained when the distance between the antennas is the biggest. The assumption that the satellite setup changed for the three different tests can be made to explain the variations of the standard deviation.

C. DYNAMIC TESTS

A displacement of at least 5 meters should be detected by a DGPS. Then, to check the ability of the system to follow a path, the GPS station is moved along a determined path. This path has the shape of an 85’ long and 25’ wide L which is about 28m*8m. At the beginning of the test, the GPS antenna is placed on one end of the path it is moved to the other side and back to the beginning by the same way. The results of this test can be seen on Figure VII.6.

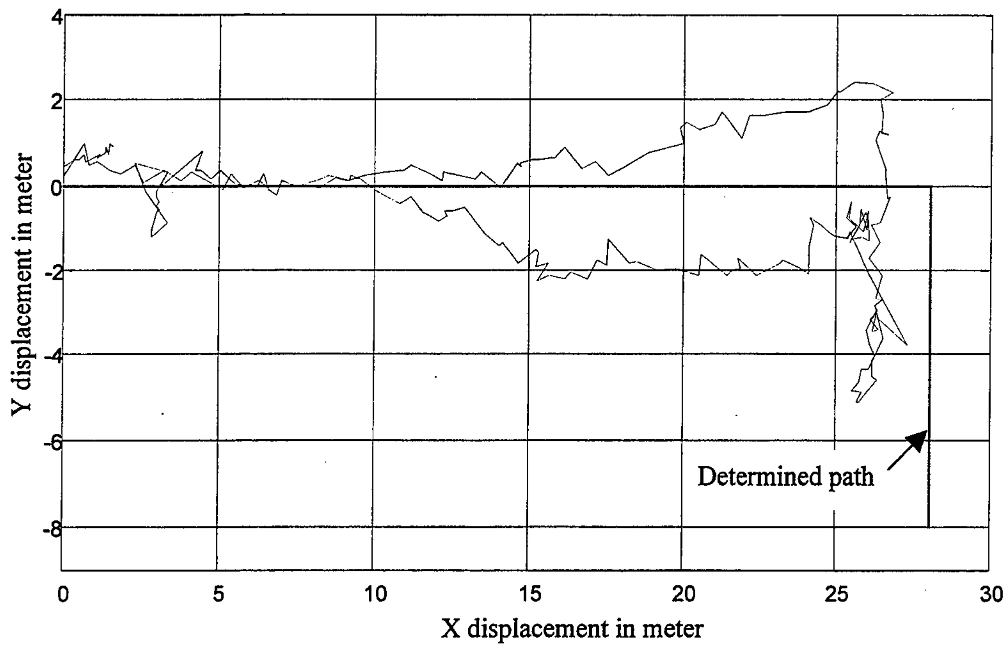


Figure VII.6: Ability of the DGPS to follow a path.

The displacements recorded by the DGPS reproduce the determined path. We can notice that the position error starts to grow at 10 m in the X-axis. This event can be attribute to the location of the test. Indeed at this place the trees are bigger and more numerous and as it as been expressed in Chapter IV, it is a source of error inducing an obstacle to the signal. However, analyzing the figure, we can notice that the position error is still less than 3m.

D. SUMMARY

Static and dynamic tests have been carried out to determine the efficiency of the DGPS. Even if the testing conditions were not the real conditions of use, the results obtained are significant. Transmitting the differential correction through radio modems has no influence on the accuracy of the position estimation. The position error remains in a range of 5m in latitude and 3m in longitude either when the correction is directly send to the GPS receiver or when it is transmitted via the radios modems. Moreover, the same accuracy is observed for the dynamic test whose purpose was to define the capability of the DGPS to follow a track.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The goal of this study was to design a DGPS for the NPS AUV in order to decrease position estimation's error. Because of the non-standardization of differential correction's frequency, the DGPS setup needs to be easily alterable in order to use differential correction no matter where the AUV's mission takes place. The solution proposed in this study is to separate the differential receiver from the GPS receiver. The differential correction will be send to the GPS receiver via radio modems. This way of transmitting the differential correction does not damage the accuracy expected by the GPS receiver's specifications. A standard deviation of about 1.6m in latitude and 1.3m in longitude has been obtained. With a different GPS receiver like the Ashtech GG24 or G12 receivers, it is possible to reduce the standard deviation to 40cm.

B. RECOMMENDATIONS

The next step of this study should be the installation of the system on the AUV and test it in the ocean in order to determine its performance in real condition of use. The maximum distance within good reception of the differential signal needs to be figure out too.

Another part of the future work is to determine a model for the GPS errors with the collected data. The purpose of this model would be to simulate the reaction of the boat before the mission in a virtual world for example and then correct the mission order if necessary.

APPENDIX A: ACRONYMS

AUV	Autonomous Underwater Vehicle
C/A code	Coarse Acquisition Code
DGPS	Differential Global Positioning System
DoD	Department of Defense (United States)
DR	Dead reckoning
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision (Latitude, Longitude)
MBARI	Monterey Bay Aquarium Research Institute
NMEA	National Marine Electronics Association
NPS	Naval Postgraduate School
PDOP	Position Dilution of Precision (3-D), sometimes the Spherical DOP
PPS	Precise Positioning Service
RBM	Rational Behavior Model
RTCM SC	Radio Technical Commission for Maritime Services Special Committee
SA	Selective availability
SPS	Standard Positioning Service
SS	Signal Strength
SV	Space Vehicle (satellite)
USCG	United States CoastGuard

APPENDIX B: SPECIFICATIONS

This appendix provides the operational, mechanical, electrical, physical, and environmental specifications for the following equipment:

- the ABX-3 beacon receiver,
- the MBL-3 DGPS loop antenna,
- the Motorola VP Oncore receiver,
- the Freewave wireless data transceiver.

1. ABX-3 beacon receiver specifications

Operational specifications	
Item	Specification
Frequency Range	283.5 - 325 kHz
Channels	2
Input Sensitivity	2.5 µV/m for 10 dB SNR @ 100 bps MSK Rate
Acquisition Time	< 1 Second Typical
MSK Bit Rate	100, 200, or Automatic
Frequency Selection	Manual or Automatic
Frequency Offset	+ 5 Hz
Dynamic Range	100 dB
Adjacent Channel Rejection	60 dB @ f_0 ± 500 Hz
Decoding	RTCM 6/8
Demodulation	MSK

Serial Interface specifications	
Item	Specification
Interface Levels	RS-232C and RS-422
Data Connector	DB9 Socket
Data Port Baud Rate	2400, 4800, or 9600 Baud
Data Output Format	RTCM SC-104, NMEA 0183
Data Input Protocol	NMEA 0183

Power Specifications	
Item	Specification
Input Voltage	9- 40 VDC
Input Current	140 mA @ 12 VDC
Power Consumption	1.7 W
Power Connector	Circular 2-pin Locking Plug

Mechanical Characteristics	
Item	Specification
Enclosure	Extruded Aluminum with Aluminum Front and Back Plates.
Length	150 mm (5.9")
Width	125 mm (4.9")
Height	51 mm (2.0")
Weight	0.64 kg (1.4 lb)
Antenna Connector	BNC Socket
Optional GPS Signal Output Connector	TNC Socket

Environmental Specifications	
Item	Specification
Storage Temperature	-40°C to 80°C
Operating Temperature	-30°C to 70°C
Humidity	95% Non-Condensing

2. MBL-3 DGPS loop antenna

Operational specifications	
Item	Specification
Frequency Range	283.5 - 325 kHz
Gain	34 dB
Pre-Amplifier	Integral Low noise Amplifier

Power Specifications	
Item	Specification
Input Voltage	4.9 - 13 VDC supplied by receiver
Input Current	25 - 35 mA

Mechanical Characteristics	
Item	Specification
Enclosure	PVC Plastic
Mounting Thread	1-14-UNS-2B
Length	128 mm (5.06")
Width	128 mm (5.06")
Height	84 mm (3.33")
Weight	450 g (1 lb)
Antenna Connector	TNC-S
Antenna Extension Cable	RG-58U, < 150 m (450 ft) in Length

Environmental Specifications	
Item	Specification
Storage Temperature	-40°C to 80°C
Operating Temperature	-30°C to 70°C
Humidity	100% Condensing

3. Motorola VP Oncore receiver

General Characteristics	Receiver Architecture	▪ 6 (or 8) channel ▪ L1 1575.42 MHz ▪ C/A code (1.023 MHz chip rate) ▪ Code plus carrier tracking (carrier aided tracking)
	Tracking Capability	▪ 6 (or 8) simultaneous satellite vehicles
Performance Characteristics	Dynamics	▪ Velocity: 1000 knots (515 m/s) > 1000 knots at altitudes < 60,000 ft. ▪ Acceleration: 4 g ▪ Jerk: 5 m/s^3
	Acquisition Time (Time To First Fix, TTff)	▪ 18 sec. typical TRFF (with current almanac, position, time and ephemeris) ▪ 45 sec. typical TTFF (with current almanac, position and time) ▪ 2.5 sec. typical reacquire
	Positioning Accuracy	▪ Less than 25 meters, SEP (without 5A) [DoD may invoke Selective Availability (SA), potentially degrading accura to 100 m (2dRMS)] ▪ DGPS accuracy 1-5 meters typical
	Timing Accuracy (1 Pulse Per	▪ 130 nanosec. observed (1s) with SA ▪ In position hold mode. < 50 nanosec. observed (1s) with SA on
	Antenna	▪ Active micro strip patch antenna Modul ▪ Powered by Receiver Module (25mA @ Vdc)
	Datums	▪ 49 std. datums, 2 user defined, default WGS-84
Serial Communication	Output Messages	▪ Latitude, longitude, height, velocity, heading, time, satellite tracking status (Motorola Binary Protocol) ▪ NMEA-0183 Version 2.00 (selected formats) available ▪ Software selectable output rate (Continuous or Poll) ▪ Broad list of command/control messages ▪ RS-232C Interface
Electrical Characteristics	Power Requirements	▪ 9 to 16 Vdc or 5 Vdc ± 0.25 V
	'Keep-Alive' BATT Power	▪ 4.75-16 Vdc; 0.3 mA (max) or ▪ 3V on-board battery: 15μA (typ.) 60μA (max)
	Power Consumption	▪ 1.3 W @ 5 Vdc; 1.8 W @ 12 Vdc
Physical Characteristics	Dimensions	▪ Receiver Board 3.94 x 2.76 x 0.7 in. (100 x 70 x 17.8 mm) ▪ Plastic Housing 4.13 x 3.03 x 1 in. (105 x 77 x 25.4 mm) ▪ Active Antenna Module 4.01 (dia.) x 0.89 in. (102 (dia.) x 22.6 mm)
	Weight	▪ Receiver Board 2.3 oz. (64 g) ▪ Receiver in Plastic Housing 3.8 oz. (107 g) ▪ Active Antenna Module 4.8 oz. (136.2 g)
	Connectors	▪ Data/Power. 10 pin (2x5) shrouded header, RF: OSX (subminiature snap-on)
	Antenna to Receiver Interconnection	▪ Single coaxial cable (6 dB max loss at L1; 1575, 42 MHz)
Environmental Characteristics	Operating Temperature	▪ Receiver Module -30°C to +85°C ▪ Active Antenna -40°C to +100°C
	Humidity	▪ 95% noncondensing +30°C to +60°C
	Altitude	▪ 60,000 ft. (18 km) ▪ > 60,000 ft. (18 km) for velocities < 1000 knots
Miscellaneous	Optional features	▪ 1 PPS timing output ▪ Raw measurement data ▪ On Board Rechargeable Lithium battery
	DGPS	▪ Differential GPS-standard software feature ▪ Motorola custom format (master output and remote input) ▪ RTCM-104 format (remote input)

4. Freewave wireless data transceiver

Range*	20 miles
RS232 Data Throughput (uncompressed)**	1200 Baud - 115.2 KBaud
RS232 Interface	Asynchronous, full duplex
System Gain	140 dB
Minimum Receiver Decode Level	-110 dBm @ 10-4 raw BER -108 dBm @ 10-6 raw BER
Operating Frequency	902 - 928 MHz
Modulation Type	Spread Spectrum, GFSK
Spreading Code	Frequency Hopping
Hop Patterns	15 (user selectable)
Output Power	1 Watt (+30 dBm)
Error Detection	32 Bit CRC with packet retransmit
Antenna	3 inch whip provided (DGR-115 model). Non-standard SMA connector allows use of external directional or omnidirectional antennas.
Power Requirements	• 10.5 - 18.0 VDC • Center Pin Positive • AC Wall Adapter Provided • May also be powered through Pin6 of DB9 connector.
Power Consumption	600 mA Transmit 100 mA Receive 180 mA Average
Connector	RS232 9 pin female. 9 pin male to 9 pin female straight through cable provided.
Unit Address	Unique, factory set
Operating Modes	• Point-to-Point • Point-to-Multipoint • Store and Forward Repeater
Operating Environment	-40° - +75°C
FCC Identifier	KNY-DGR-115
DOC (Canada) Identifier	2329 101 340A

* Line of sight distance using supplied whip antennas
** Throughput measured assuming 75% frequency availability

	DGR-115	DGR-115H
Enclosure	Plastic	Milled Aluminum
Dimensions	41mmH x 99mmW x 188mmL	28mmH x 102mmW x 205mmL
Weight	340 grams	560 grams

APPENDIX C: NMEA FORMAT

This appendix identifies the selection of NMEA 0183 command and status query messages valid for the ABX-3. The latest version is available by contacting:

National Marine Electronics Association
NMEA Executive Director
P. O. Box 50040, Mobile, Alabama 36605, USA
Tel (205) 473-1793   Fax (205) 473-1669

Information on the RTCM SC104 format is available at:

Radio Technical Commission for Maritime Services
Post office Box 19087
Washington, DC 20036

NMEA MESSAGE ELEMENTS

All NMEA 0183 messages possess a common structure, including a message header, data fields, and a terminating carriage return and line feed.

Example: $GPYYY,xxx,xxx,xxx ... <CR><LF>

The table below displays the elements of this example message.

Element	Description
$GP	Message Identifier Indicating a GPS Related Message
yyy	Type of GPS Message
Xxx	Variable Length Message Fields
<CR>	Carriage Return
<LF>	Line Feed

ABX-3 SUPPORTED MESSAGES

The ABX-3 supports the NMEA commands and queries listed in the following Table.

Message description	Description
Commands	
$GPMSK (Full Manual Tune)	Sets the receiver into Full Manual Tune Mode
$GPMSK (Partial Manual Tune)	Sets the receiver into Partial Manual Tune Mode
$GPMSK (ABS Mode)	Sets the receiver into Automatic Beacon Search Mode
$PCSI,4 (Proprietary)	Erases the Global Search table forcing a new search
$PCSI,5 (Proprietary)	Sets the baud rate of the ABX-3 communication port
$PCSI,6 (Proprietary)	Reserved
$PCSI,7 (Proprietary)	Reserved
$PSLIB (Proprietary)	Sets the frequency and MSK bit rate of the ABX-3
Queries	
$GPCRQ Operation Query	Queries the receiver for operation parameters
$GPCRQ Performance Query	Queries the receiver for performance parameters
$PCSI,0 (Proprietary)	Lists available proprietary $PCSI commands and queries
$PCSI,1 (Proprietary)	Displays receiver operating parameter status
$PCSI,2 (Proprietary)	Queries the receiver for operation parameters
$PCSI,3 (Proprietary)	Outputs receiver search information

NMEA 0183 COMMANDS

This section discusses the standard and proprietary NMEA 0183 commands accepted by the ABX-3.

- **Full Manual Tune Command ($GPMSK)**

  This command instructs the ABX-3 to tune to a specified frequency and MSK Rate. It has the following form:

  $GPMSK,fff.f,M,ddd,M,n<CR><LF>

- **Partial Manual Tune Command ($GPMSK)**

  This command instructs the ABX-3 to tune to a specified frequency and automatically select the correct MSK rate. It has the following form:

  $GPMSK,fff.f,M,,A,n<CR><LF>

- **Automatic Beacon Search Command ($GPMSK)**

  This command initiates the ABX-3 automatic mode of operation in which the receiver operates without operator intervention, selecting the most appropriate beacon station. This command has the following format:

  $GPLMSK,,A,,A,n<CR><LF>

- **Wipe Search Command ($PCSI,4)**

The Wipe Search command instructs the ABX-3 to erase all parameters within the beacon almanac and to initiate a new Global Search to identify the beacon signals available for a particular area. The command has the following form:

$PCSI,4<CR><LF>

- **Baud Rate Change Command ($PCSI,5)**

This proprietary $PCSI command is reserved for use with the ABX-3.

$PCSI,5,r<CR><LF>

- **Tune Command ($PSLIB)**

A majority of Garmin hand-held and fixed-mount GPS receivers output this non-standard command from the BEACON RCVR feature of the INTERFACE menu. It instructs both the connected beacon receiver to tune to the specified frequency and MSK Rate. The command has the following form:

$PSLIB,fff.f,ddd<CR><LF>

NMEA 0183 QUERIES

This section discusses the standard and proprietary NMEA 0 1 83 queries accepted by the ABX-3 receiver.

- **Receiver Operating Status Query ($GPCRQ)**

This standard NMEA query prompts the ABX-3 receiver for its operational status. It has the following format:

$GPCRQ,MSK<CR><LF>

- **Receiver Performance Status Query ($GPCRQ)**

This standard NMEA query prompts the ABX-3 receiver for its performance status:

$GPCRQ,MSS<CR><LF>

- **Receiver Help Query ($PCSI,C)**

This command queries the ABX-3 receiver for a list of valid proprietary $PCSI commands:

$PCSI,0<CR><LF>

- **ABX-3 Status Line A, Channel 0 ($PCSI,1)**

This commands the ABX-3 to output a selection of parameters related to the operational status of its primary channel. It has the following format:

$PCSI,1<CR><LF>

- **ABX-3 Status Line B, Channel 1 ($PCSI,2)**

This commands the ABX-3 to output a selection of parameters related to the operational status of its secondary channel. It has the following format:

$PCSI,2<CR><LF>

- **Receiver Search Dump ($PCSI,3)**

This query commands the ABX-3 to display the search information used for beacon selection in Automatic Beacon Search mode. The output has three frequencies per line.

$PCSI,3<CR><LF>

APPENDIX D: C-CODE

The following code is the C-code enable to read the data transmit by the GPS. On the AUV computer, this file is named GPS.c.

```
/* ------------------------------------------------------------------
   File: GPS.c

   Purpose:
      This code read the Motorola Binary formatted messages send by
      the Motorola VP Oncore receiver trough an RS-232 serial port
      and transcribe them into understandable value.
   ------------------------------------------------------------------
*/

#include <stdio.h>   /* Standard input/output definitions */
#include <string.h>  /* String function definitions */
#include <unistd.h>  /* UNIX standard function definitions */
#include <fcntl.h>   /* File control definitions */
#include <errno.h>   /* Error number definitions */
#include <termios.h> /* POSIX terminal control definitions */
#include <sys/time.h>
#include <sys/select.h>

#define CR 0x0d /* ASCII Carriage-Return (CR) */
#define LF 0x0a /* ASCII Line-Feed (LF) */

#define TRUE  1
#define FALSE 0
#define pi 3.141592654

/* Hexadecimal - Character

| 00 NUL| 01 SOH| 02 STX| 03 ETX| 04 EOT| 05 ENQ| 06 ACK| 07 BEL|
| 08 BS | 09 HT | 0A NL | 0B VT | 0C NP | 0D CR | 0E SO | 0F SI |
| 10 DLE| 11 DC1| 12 DC2| 13 DC3| 14 DC4| 15 NAK| 16 SYN| 17 ETB|
| 18 CAN| 19 EM | 1A SUB| 1B ESC| 1C FS | 1D GS | 1E RS | 1F US |
| 20 SP | 21  ! | 22  " | 23  # | 24  $ | 25  % | 26  & | 27  ' |
| 28  ( | 29  ) | 2A  * | 2B  + | 2C  , | 2D  - | 2E  . | 2F  / |
| 30  0 | 31  1 | 32  2 | 33  3 | 34  4 | 35  5 | 36  6 | 37  7 |
| 38  8 | 39  9 | 3A  : | 3B  ; | 3C  < | 3D  = | 3E  > | 3F  ? |
| 40  @ | 41  A | 42  B | 43  C | 44  D | 45  E | 46  F | 47  G |
| 48  H | 49  I | 4A  J | 4B  K | 4C  L | 4D  M | 4E  N | 4F  O |
| 50  P | 51  Q | 52  R | 53  S | 54  T | 55  U | 56  V | 57  W |
| 58  X | 59  Y | 5A  Z | 5B  [ | 5C  \ | 5D  ] | 5E  ^ | 5F  _ |
| 60  ` | 61  a | 62  b | 63  c | 64  d | 65  e | 66  f | 67  g |
| 68  h | 69  i | 6A  j | 6B  k | 6C  l | 6D  m | 6E  n | 6F  o |
| 70  p | 71  q | 72  r | 73  s | 74  t | 75  u | 76  v | 77  w |
| 78  x | 79  y | 7A  z | 7B  { | 7C  | | 7D  } | 7E  ~ | 7F DEL|
*/
```

```
/*
 Example Output:

40404561050707cf1605040006fde107d9e9e3e5d9de43ffff
ea1dfffff5b000000000000000080005005400060 05d000a00
550011005a00160059001700540 01a0055001e005800083f
*/

   FILE *outfp;
   FILE *outmat,*outsat;

/*
   GPS Output Format:           Variable Name   Units      Type
*/

main()
{
   /* Declaration */
   int k,i,j,fid,n_loops,cpt;
   int NOT_CR,channel;
   int New_message;
   int pos_control;
   int neg_lat,neg_longitude,lat;
   int longitude,longdeg,longmin,longsec,longmsec,essai;
   int latdeg,latmin,latsec,latmsec;
   int hours, tminutes, tseconds, tfract;
   char x_buff[1],mem[1],mess[200],position_mess[4];
   char month[1],day[1],diff[1], nsat[1];
   char sat_tracked[1],TDOP[1],sat_id[8],mode[8],SS[8],used[8];
   char *x;              /* This is a pointer to a 1 Byte location */
   unsigned short year, DOP;
   double mlong,mlat,time,fract,height;

   /* Open serial port */
   fid = open("/dev/ser1", O_RDWR | O_NOCTTY);
   if (fid == -1)
   {
     printf("open_port: Unable to open \n");
     exit(0);
   }

   /* Open files to record the data */
   outmat = fopen("GPSmat.d","w");
   outsat = fopen("GPSsat.d","w");

   /* Enter the number of loop to run the program */
   printf("Input n_loops\n");
   scanf("%d",&n_loops);

   time = 0;
   for(i=0;i<n_loops;++i)
   {
      /*Find the <CR><LF> means end of message*/
      read(fid,x_buff,1);
      cpt=0;
      New_message= FALSE;
      NOT_CR= TRUE;
```

```
while (New_message == FALSE)
{
   if (x_buff[0] == CR)
   {
      mem[0]= x_buff[0];
      read(fid,x_buff,1);

      if (x_buff[0] == LF)
      {
         New_message = TRUE;
      }
      else
      {
         mess[cpt]= mem[0];
         cpt=cpt+1;
         NOT_CR= FALSE;
      }
   }
   if (New_message == FALSE)
   {
      if (NOT_CR)
      {
         mess[cpt]=x_buff[0];
         cpt=cpt+1;
         read(fid,x_buff,1);
      }
      else
      {
         NOT_CR=TRUE;
      }
   }
}

/* Define if it is a message for position */
pos_control = TRUE;
k=0;

position_mess[0]= 0x40;
position_mess[1]= 0x40;
position_mess[2]= 0x45;
position_mess[3]= 0x61;

while (pos_control & k<4)
{
   pos_control= (mess[k] == position_mess[k]);
   k= k+1;
}

/* Transcription of the message */
if (pos_control)
{
   printf("\n");

   /* Date */
   month[0] = mess[4];
   day[0] = mess[5];
   x = &year;           /* x points to the address of year */
```

```
x[0] = mess[7];
x[1] = mess[6];

/* Time */
x = &hours;
x[0] = mess[8];
x[1] = 0;
x[2] = 0;
x[3] = 0;
x = &tminutes;
x[0] = mess[9];
x[1] = 0;
x[2] = 0;
x[3] = 0;
x = &tseconds;
x[0] = mess[10];
x[1] = 0;
x[2] = 0;
x[3] = 0;
x = &tfract;
for (k=0;k<=3;++k)
{
   x[k] = mess[(14-k)];
}
time = (hours*3600 + tminutes*60 + tseconds);

/* Dilution of precision */
x = &DOP;
x[0] = mess[36];
x[1] = mess[35];
DOP = DOP/10;
TDOP[0] = mess[37];

/* Number of visible satellites */
nsat[0] = mess[38];

/* Number of satellites tracked */
sat_tracked[0] = mess[39];

/* Differential signal */
diff[0] = mess[72] & 0x04;


/*Latitude */
x = &lat;            /* x points to the address of lat */
for (k=0;k<=3;++k)
{
   x[k] = mess[(18-k)];
}

/* Longitude */
x = &longitude;         /* x points to the address of long */
for (k=0;k<=3;++k)
{
   x[k] = mess[(22-k)];
}
/* Conversion of latitude and longitude into degrees,
```

```
minutes, secondes and miliseconde */
latdeg = lat/3600000;
mlat = lat*(2*pi*6371/(360*3600));
if (lat < 0)
{
   neg_lat = -1 * lat;
}
else
{
  neg_lat = lat;
}
latmin=(neg_lat % 3600000)/ 60000;
latsec=((neg_lat % 3600000)% 60000)/1000;
latmsec=((neg_lat % 3600000)% 60000)%1000;
longdeg = longitude/3600000;
mlong = longitude * 0.02498849593; /* correction of
                                      the radius */
if (longitude < 0)
{
    neg_longitude = -1 * longitude;
}
else
{
  neg_longitude = longitude;
}
longmin=(neg_longitude % 3600000)/ 60000;
longsec=((neg_longitude % 3600000)% 60000)/1000;
longmsec=((neg_longitude % 3600000)% 60000)%1000;

/* Height */
x = &h;           /* x points to the address of height */
for (k=0;k<=3;++k)
{
   x[k] = mess[(26-k)];
}
height = h/100;

/* Satellite information */
for (k=0;k,k<=7;++k)
{
   sat_id[k] = mess[(40+k*4)];      /* Satellite ID */
   mode[k] = mess[(41+k*4)];     /* Channel tracking mode */
   SS[k] = mess[(42+k*4)];          /* Signal Strengh */
   if ((mess[(43+k*4)] & 0x80) == 0x80)
   {
      used[k] = '1';  /* Using for position fix or not */
   }
   else
   {
      used[k] = '0';
   }
}
```

```
            /* record the data on files */
            fprintf(outmat,"%f %f %f %d %d %d %d\n", mlat, mlong, time,
            diff[0], sat_tracked[0],DOP,TDOP);
            for (k=0;k<=7;++k)
            {
               fprintf(outsat,"%d %d %c ",sat_id[k],SS[k],used[k]);
            }
            fprintf(outsat,"\n");

            /* Print the data on the screen */
            printf("\n");
            printf(" Date: %d/%d/%d\n",month[0],day[0],year);
            printf(" Time: %dh %dmin %d.%dsec\n", hours, tminutes,
            tseconds, tfract);
            printf("\n");
            printf(" Number of visible satellites:%d\n",nsat[0]);
            printf(" Number of satellites tracked:%d\n",sat_tracked[0]);
            printf(" Dilution of precision: %d ",DOP);
            if (TDOP[0] = 0x01)
            {
               printf("HDOP\n");
            }
            else
            {
               printf("PDOP\n");
            }
            printf("\n");
            printf("Latitude: %d    %d^%d'%d''%d\n", lat, latdeg,
            latmin, latsec, latmsec);
            printf("Longitude: %d   %d^%d'%d\"%d\n", longitude, longdeg,
            longmin, longsec, longmsec);
            printf("Height (GPS): %f (m)\n",height);
            printf("\n");
            if (diff[0] == 0x04)
            {
               printf("          Differential signal\n\n");
            }
            else
            {
               printf("          Not differential signal\n\n");
            }
            printf(" Channel     ID     Mode     SS     Used\n");
            for (k=0;k<=7;++k)
            {
               channel= k+1;
               printf("%6i %9d %7d %7d       %c\n", channel, sat_id[k],
               mode[k], SS[k],used[k]);
            }
        }
    }
}
```

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